Under the weather: The influence of land-use and climate on surface water fecal contamination

by

Jacques St Laurent
BSc, University of Exeter, 2009

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

MASTER OF SCIENCE

in the Department of Biology

© Jacques St Laurent, 2012
University of Victoria

All rights reserved. This thesis may not be reproduced in whole or in part, by photocopy or other means, without the permission of the author.

Supervisory Committee

Under the weather: The influence of land-use and climate
on surface water fecal contamination

by

Jacques St Laurent
BSc, University of Exeter, 2009

Supervisory Committee

Dr. Asit Mazumder (Department of Biology)
Supervisor

Dr. Klaas Broersma (Department of Biology)
Departmental Member

Dr. Rick Nordin (Department of Biology)
Departmental Member

Abstract

Supervisory Committee

Dr. Asit Mazumder (Department of Biology)
Supervisor

Dr. Klaas Broersma (Department of Biology)
Departmental Member

Dr. Rick Nordin (Department of Biology)
Departmental Member

The risk of waterborne infections acquired from the consumption of contaminated water is related to changes in source water fecal contamination, which is often influenced by land-use and hydro-meteorological conditions in the surrounding watershed. The impact of land-use composition on surface water contamination was explored in order to determine the risk of surface water contamination associated with land-use change. Highest contamination was observed in watersheds characterized by more than 12.5% agricultural and more than 1.6% urban land (mean fecal coliform (FC) concentration of these 5 sites = 135 CFU 100ml^{-1} while the British Columbia (BC) raw water quality guideline = 100 CFU 100ml^{-1}). Contamination increased exponentially, and violated BC raw water quality guidelines with greater frequency, in relation to greater agricultural land in the upstream watershed. Additional factors, such as sewage treatment plants, low dilution in smaller streams, and higher temperatures were also associated with greater contamination. These results indicate the high level of risk posed by agricultural and urban development and the need for source water protection.

Fecal contamination levels in source water are also influenced by rainfall and snowmelt-induced surface runoff that transport diffuse fecal contaminants into surface water. Seasonal levels of fecal contamination in surface water was related to the watershed hydro-climatic regime for around half of the watersheds examined. Watersheds with snowmelt-dominant (SD) runoff regimes showed stronger evidence of hydro-meteorological variability driving seasonal contamination levels than those with rainfall and snowmelt-influenced (RSI) and rainfall-dominant (RD) runoff regimes, and thus are more prone to experiencing changes to seasonal variability resulting from climate change. Projected increases in mean annual temperatures of between 1.7^{0}C and 4.0^{0}C towards the end of the 21st century will alter existing runoff regimes within watersheds. For SD watersheds that remain below freezing and continue to accumulate snowpack during the cold season, transport of fecal contamination will likely occur earlier in the year with greater intensity. Fecal coliform transport in summer is likely to decrease, especially in SD watersheds in which fecal contamination is driven by summer rainfall events. Snowmelt-dominant watersheds transitioning toward a RD runoff regime will experience less contamination during spring but increased contamination during late fall and winter. The extent to which these changes in runoff regime will influence surface water fecal contamination will vary among watersheds. Further investigation is required to identify factors that enhance or mitigate the association of surface water fecal contamination with rainfall and snowmelt-induced runoff in order to identify specific site vulnerability to changing seasonal contamination levels.

Total precipitation within BC is projected to increase by 20-30% towards the end of the 21st century. The association of annual FC variability with snowmelt and rainfall

variability was examined in order to assess the capacity of such increases to raise the level of surface water fecal contamination. Greater total annual and seasonal rainfall and/or river discharge increased surface water fecal contamination for 58% (11/19) of the sites examined. Hydro-meteorological variability influenced FC concentration during winter, the season of greatest precipitation, and spring, the season of greatest snowmelt, but not during summer or fall. Reduced contamination levels during the El Niño event in 2002/03 were associated with a mean reduction in river discharge during spring and summer. These associations suggest that the risk of increased surface water fecal contamination in response to higher precipitation is likely to be greatest in winter for RD watersheds and spring for SD watersheds, although the magnitude of impact will vary among sites.

Climate change and land-use activities within watersheds have the capacity to alter the timing and amount of surface water fecal contamination. These factors are likely to act synergistically by increasing the presence and transport of fecal contaminants within watersheds. Such relationships should be carefully considered to aid the assessment and mitigation of the risk of source water contamination associated with land-use and climate change.

Table of Contents

List of Tables

List of Figures

Definition of terms

1. Anthropogenic:	Resulting from human influence
2. Climate change:	Long-term change from the climate norm
3. Hydrograph:	Mean pattern of river discharge over time
4. Hydro-meteorological:	Surface water and atmospheric parameters
5. Impacted land:	Land with elevated fecal contamination
6. River discharge:	The rate of flow for a stream or river
7. Runoff regime:	Mean pattern of overland and subsurface flow

Acknowledgements

First and foremost I am grateful to Dr. Asit Mazumder, my supervisor, who has provided me with the opportunity to undertake this research and provided unfailing support throughout. I wish to also thank my committee members, Dr. Klaas Broersma and Dr. Rick Nordin, for their generous expenditure of time and effort on my behalf. I am delighted to be able to acknowledge my comrade, Tim Hurley, whose solidarity has been unwavering and inestimably valuable. The many individuals who have passed through the Mazumder lab, and those who remain, have been kind and generous in many ways. In particular, I am grateful to John Zhu and Claire Perrin for their insightful advice.

I am grateful to Canada for a warm welcome. This research was made possible by the data provided by Environment Canada and the BC Ministry of Environment. Thank-you to everyone who helped me obtain data and took an active interest in the project. This work was funded by the National Science and Engineering Research Council of Canada (NSERC) through the Res’eau Waternet Research Network, and by the Public Health Agency of Canada through a grant held by Dr Asit Mazumder.

On a more personal note, I would like to thank the communities that I am fortunate enough to be a part of here in Victoria, BC, for their unconditional kindness, generosity, and support. The Franciscan Friars, the Mindfulness Community of Victoria, and The Iyengar Yoga Centre of Victoria have provided the foundation that has supported me through this time. I am profoundly grateful to Anthony De Mello SJ, Thich Nhat Hanh, and B.K.S. Iyengar whose courage and creativity are a constant inspiration. Lastly, I wish to extend my gratitude to innumerable friends and family, especially Sarah McJarvis, who have brought meaning and value to this period of my life.

Dedication

This work is ultimately dedicated to those for whom drinking safe water without fear of infection is a luxury they cannot take for granted, as I often do.

Chapter 1 Introduction

The old adage “under the weather” originated from observations that disease incidence is associated with weather patterns. Hippocrates (~460 to 377 B.C.) was the first known person to record links between disease outbreaks and hydro-meteorological variability (NRC, 2001). More recently, in 1882, Robert Koch elaborated the germ theory of disease, superseding the notion that disease is transmitted by poisons in the wind. Knowledge about pathogenic microorganisms has developed and led to a re-focus of scientific attention on the influence of climate variability, which effects their distribution, growth, and survival. Climate change is causing a shift in temperature and precipitation patterns, which is altering the distribution and prevalence of certain pathogens, especially those that are waterborne (Patz *et al.,* 2005 and 2008a).

Pressures due to climate change and increased anthropogenic alterations to the landscape have the potential to increase surface source water fecal contamination (Delpla *et al.,* 2009). Surface water fecal contamination is principally determined by land-use composition and hydro-meteorological variability. These factors can alter the presence and transport of fecal contamination within a watershed (Kay *et al.,* 2008). Fecal contamination of source water is associated with a higher incidence of waterborne disease, which is transmitted through contaminated drinking water (e.g. Aramini *et al.,* 1999 and 2000). Managing the risk associated with source water contamination can be aided by anticipating the impact of changes in climate and land-use on contamination levels. The influence of these factors on fecal contamination, however, has proved challenging to quantify and, therefore, estimates of climate and land-use contributions to surface water fecal contamination are associated with high degree of uncertainty

(Schaffter and Parriaux, 2002; Schaffter *et al.,* 2004; Wilkes *et al.,* 2009). Diffuse fecal contaminants produced by land-use activities within a watershed are not easy to measure or control, and hydro-meteorological influences on contaminant transport tend to be highly variable (Schaffter *et al.,* 2004; Signor *et al.,* 2005; Kloot, 2006). Consequently, anticipating the influence of climate change on source water fecal contamination is an exigent task. Such efforts are required, however, in order to mitigate source water quality degradation and maintain the provision of fresh clean drinking water (Davies and Mazumder, 2003; Charron *et al.,* 2004).

1.1 The burden of waterborne disease

Seven percent of the global disease burden and around 2.4 million deaths could be prevented every year through the provision of safe water drinking water and better sanitation (Bartram and Cairncross, 2010). In Canada alone, 288 waterborne disease outbreaks were officially recorded between 1974 and 2001, although the true figure is likely far greater (Schuster *et al.,* 2005). A single waterborne disease outbreak can be devastating for public health. This can be illustrated by a few recent examples. In 1993 an outbreak of *Cryptosporidium* that originated in the drinking source of Milwaukee, Wisconsin, caused more than 400,000 cases of gastroenteritis (MacKenzie *et al.,* 1994). In 1994 the world's largest *Toxoplasmosis* outbreak was transmitted through the municipal water supply in Victoria, British Columbia (BC), resulting in the infection of between 2900 and 7700 individuals (Aramini *et al.,* 1999). Most markedly, more than 2000 illnesses and 7 deaths resulted from Canada's highest profile waterborne disease outbreak "The Walkerton Water Tragedy" that occurred in Ontario, in May 2000 (O'Connor, 2002a). The rise in public awareness generated by these events has prioritised the provision of safe drinking water at provincial, territorial, federal, and municipal levels of government (Perdek *et al.,* 2003).

Waterborne infections represent a significant burden to Canadian health. The number of individual cases in Canada is greatly underestimated, as most go unreported. MacDougall *et al.,* (2007) conducted a study that suggested an average of 350 cases of gastroenteritis occur in BC for every one case captured in provincial communicable disease statistics. These estimates correspond to 19.7 million sick days per year in BC and a resultant economic burden of 514.2 million Canadian Dollars (MacDougall *et al.,* 2007; Henson *et al.,* 2008). A parallel study in Hamilton, Ontario, reported a similar mean estimate of 313 infections per reported case, corresponding to over 12 million infections a year in this province (Majowicz *et al.,* 2005; Sargeant *et al.,* 2008). Canada wide, around 8000 confirmed cases of waterborne infection were reported due to contaminated drinking water between 1974 and 1996, however, the true number can be anywhere between 10 and 1000 time greater (Edge *et al.,* 2008).

Fecal contamination of drinking source water remains a primary health concern. This was illustrated by a report published by the Canadian Medical Association, which tallied 1766 boil water advisories in effect across Canada (Eggertson, 2008). This demonstrates a critical need to develop a better understanding of the factors that influence source water fecal contamination.

1.2 Factors associated with waterborne disease outbreaks

Four conditions must coincide in order for waterborne infections or a disease outbreak to occur:

1. A pathogen source, e.g. infected humans, domestic animals, and/or wildlife;

2. Transport of the pathogen into source water;
3. Evasion of, or capacity of the pathogen to withstand disinfection; and
4. Ingestion of the pathogen by susceptible persons.

The probability of the above conditions occurring increases greatly during hydro-meteorological events, such as heavy rainfall, high river discharge, and flooding. Such events have been shown to greatly increase turbidity and pathogen concentrations in surface waters (Kistermann *et al.,* 2002; Dorner, 2007, Kay *et al.,* 2008). This causes physical and managerial stress on water supply systems, reducing treatment efficiency and increasing pathogen survival (Perdek *et al.,* 2003; Lemmen, 2008). These factors were associated with outbreaks of gastrointestinal disease in Milwaukee and Walkerton, and are correlated with endemic gastroenteritis variability within the Metro Vancouver region (Aramini *et al.,* 2000; Stirling *et al.,* 2001; O'Connor, D. 2002a; MacKenzie *et al.,* 2004).

The Walkerton waterborne disease outbreak provides a clear illustration of how periodic heavy rainfall can lead to water treatment failure and subsequent waterborne infections. Intense rainfall generated surface runoff transported nearby manure into the municipal wells used for drinking source water. This led to high concentrations of verotoxigenic *Escherichia coli* in the city's water (O'Connor, 2002b). Data from the event showed a lag of 3-4 days between the precipitation event and surges in the number of confirmed cases of gastrointestinal infection, which is consistent with the incubation period for verotoxigenic *E. coli* (Greer *et al.,* 2008).

Curriero *et al.* (2001) demonstrated the interrelationship between precipitation and waterborne disease on a broader scale. They showed that 68% of waterborne disease outbreaks in the US (from 1948 -1994) were preceded by heavy precipitation events (top 80th percentile). A similar study performed on Canadian data by Thomas *et al.* (2006) affirmed this trend. The chance of waterborne illness was shown to more than double during the six weeks following an extreme rainfall event. The data set obtained by Thomas *et al.* (2006) illustrates a marked seasonality in the frequency of waterborne disease outbreaks in Canada (Fig. 1.2.1).

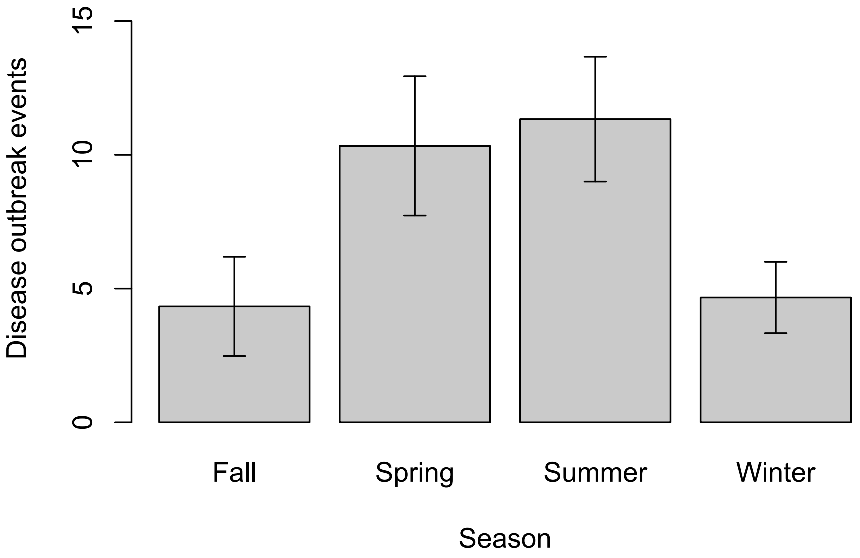

Figure 1.2.1 The mean frequency of waterborne disease outbreaks (n=92) in each season (calculated from monthly totals with error bars showing standard error) that occurred in Canada between 1975 and 2001 (Data from Thomas *et al.,* 2006).

The majority of outbreaks in Canada occur during the spring and summer (Fig. 1.2.1). Spring snowmelt events and summertime periodic intense rainfall events can generate pathogen rich and highly turbid surface runoff (Schuster *et al.,* 2005). High turbidity and pathogen loading into source water from runoff can result in the failure of water treatment to neutralise waterborne pathogens, which can account for the higher frequency of outbreaks in spring and summer.

1.3 Land-use and surface water fecal contamination

Different land-use and associated activities determine the presence and distribution of fecal sources within a watershed (Ferguson *et al.*, 2003b). Other factors, such as geology, riparian vegetation, wastewater treatment, and land management practices, can influence the proportion of this fecal contamination within a watershed that is transported into source water. Figure 1.3.1 illustrates some of the most significant factors associated with different land-use types that influence downstream fecal contamination.

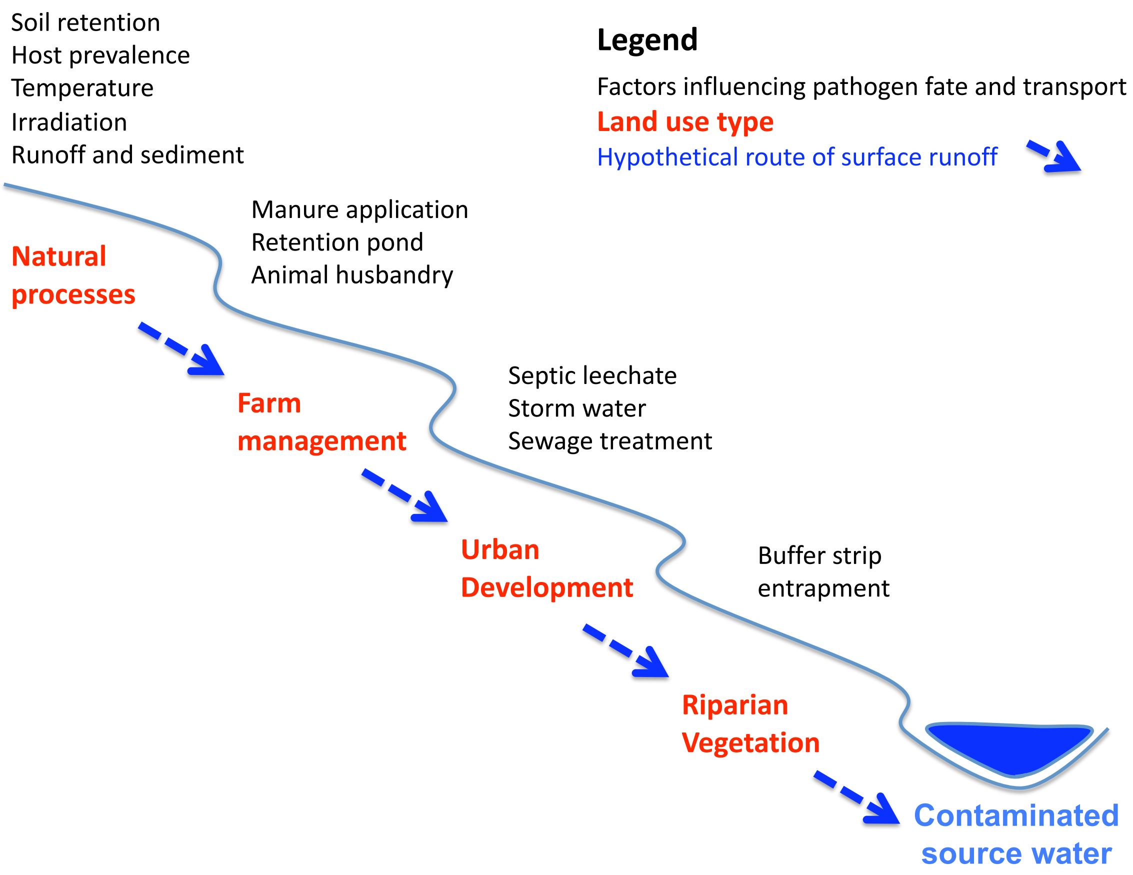

Figure 1.3.1 A conceptual model of watershed factors that influence fecal coliform contamination of drinking source water (adapted from Ferguson *et al.*, 2003b)

Sources of fecal contamination may be confined to a discrete point, for example a sewage outlet, or diffuse, as in the case of feces produced by wildlife (Perdek *et al.,* 2003). Point sources tend to release high concentrations of fecal contamination into the environment at a specific location, whereas diffuse sources are more dispersed, making them difficult to quantify and manage on a watershed scale (Kloot, 2006). Table 1.3.1 lists some of the most common sources of fecal contamination in watersheds and identifies them as either point of diffuse.

Table 1.3.1 Fecal coliform sources, designated as point or diffuse, commonly occurring in watersheds (adapted from Tyrrel and Quinton, 2003)

Source of fecal contamination	Type
Wastewater/sewage treatment plants	Point
Storm water discharge and sewage system overflow	Point
Discharge from septic tank systems	Point
Sewage sludge and livestock wastes applied to land	Point/Diffuse
Livestock feces	Diffuse
Recreational activities within the watershed	Diffuse
Defecation by wildlife	Diffuse

Certain land-use types within a watershed are associated with surface water fecal contamination due to the presence of organisms that produce fecal waste. Fecal contamination produced by wildlife can be considered as the natural baseline level, which can be high enough to exceed raw water quality standards (Perdek *et al.,* 2003). However, anthropogenic sources greatly amplify fecal contamination levels (Garcia-Armisen and Servais, 2006; Coffey *et al.,* 2010). Activities, such as livestock farming, manure application, and recreational activities can generate large quantities of concentrated fecal waste (Tate *et al.,* 2004; Meays *et al.,* 2006b; Arnone and Walling, 2007; Li *et al.,* 2009).

Urban areas contain concentrated sources of enteric pathogens in sanitary and combined sewer systems. These are vulnerable to overflow when subject to storm water in-flow and may release contaminats due to infiltrating groundwater through cracked and broken pipes and equipment failure (Arnone and Walling, 2007). Agricultural land is associated with fecal waste produced from livestock, for example, cows, pigs, and poultry (Sigua, 2010). Canadian livestock produced about 177 million tonnes of manure in 2001, roughly equivalent to the fecal waste of 2.4 billion people (Unger, 2008).

The survival and transportation of fecal pathogens from land surfaces into source water is influenced by a large number of abiotic factors. Survival tends to be enhanced by low temperatures, low UV, moderate pH, and high nutrient levels. Transport is facilitated by intact and structured soils with macropores and a large grain size, frequent and high intensity rainfall, and high river discharge (Ferguson *et al.,* 2003a).

Anthropogenic alteration of the watershed greatly influences pathogen survival and transport. Removal of vegetation reduces infiltration, amplifying runoff, turbidity, and pathogen loading into downstream source waters (Atwill *et al.,* 2002). In contrast, riparian vegetated buffer strips are very effective at removing pathogens in agricultural runoff (Tate *et al.,* 2004). Hydraulic modifications in urban areas, such as gutters, storm sewers, and pavements, enhance the transport of fecal contaminants into source waters by increasing the flow velocity, volume, and total pollutant load of runoff (Field and Sullivan, 2003).

Kay *et al.* (2008) showed evidence of land-use influencing surface water fecal coliform (FC, an indicator bacteria used to measure fecal contamination) variability among watersheds in the UK. An increase in FC concentration in relation to greater urban development within a watershed identified the impact of urban activity on surface water contamination. However, the ranges of values in some rural sites were as great as that of urban sites, which demonstrated that FC concentration is highly variable and cannot be easily anticipated on the basis of land-use composition. The one exception to this was woodland-dominated sub-catchments, in which surface water was consistently less contaminated. Dairy farming was associated with increased fecal contamination in rural areas. Mean FC concentration during high flow conditions increased in relation to the extent of improved pasture (land for livestock grazing) within rural sub-catchments ($r^2=0.42$, $p<0.001$). Unexplained variance was mainly ascribed to point sources of contamination, such as sewerage infrastructure, and differences in weather conditions between studies.

Canada's heavy dependence on surface water for drinking sources makes it especially vulnerable to the influence of land-use on fecal contamination. Approximately three-quarters of all Canadian drinking water is extracted from surface water, and urban and suburban centers rely on it almost exclusively (Ritter *et al.,* 2002). Surface waters are more vulnerable to contamination from surface and subsurface runoff, leaching, and direct discharge than ground water sources. More than 3500 surface water systems are used as drinking sources, often untreated, within BC alone (Eggertson, 2008).

1.4 Hydro-meteorological factors and surface water fecal contamination

Associations between hydro-meteorological (surface runoff, river discharge, precipitation, and temperature) and FC variability in surface water can be examined over various periods, from single events to inter-annual variability. Hydro-meteorological events influence FC concentration by altering the volume of surface runoff, which has the capacity to transport fecal contaminants into surface water. This process is influenced by a multitude of factors within the watershed, which may account for the high variability observed in relationships between hydro-meteorological and FC concentration variability at different spatial and temporal scales. Rainfall and snowmelt tends to be positively correlated with surface water FC concentration, however, negative relationships have been observed. This is perhaps due to dilution effects or the influence of polluting activities during periods of low intensity precipitation.

Single precipitation events can cause short-term and localized increases in FC concentration. Meays *et al.* (2006a) examined diurnal FC concentration variability in three streams near Vernon, BC. Variability was high throughout the 24-hour study period in each stream, but greatest following precipitation, which was thought to release contaminants from sediments in the stream and increase loading from the surrounding catchment area. A similarly rapid response was observed in the Grand River watershed in Ontario, where FC concentration increased by more than one to two orders of magnitude following the onset of precipitation (Dorner *et al.,* 2007). This response was only observed during greater rainfall events, which generated trends in FC concentration characterized by a long period of slowly declining FC levels following the event. Similarly, storm-water generated by heavy precipitation events increased the load of contaminants into coastal water in North Carolina, which increased fecal contamination beyond water quality guidelines (Parker *et al.,* 2010).

The influence of seasonal hydro-meteorological variability can result in seasonal FC concentration variability, although, at larger temporal scales relationships become more variable. Dorner *et al.* (2007) observed lower FC concentrations during the winter and early spring months. Mean FC concentration increased in late spring and summer concurrent with snowmelt-induced runoff, but were highly variable and not strongly related to runoff variability. The potential association with monthly rainfall variability was not considered. Although not significantly different between seasons, FC concentration was highest during months with greater rainfall in the agricultural Pinhal River watershed, in Santa Catarina, Brazil (Sigua *et al.,* 2010). Greater transport of suspended bacteria in subsurface flow was thought to increase the load of microbial pollutants into the Pinhal River during high rainfall. Similarly, in North Carolina, coastal FC concentrations were highest in summer and fall, corresponding to warmer temperatures, greater rainfall, and increased human activities (Parker *et al.,* 2010).

This relationship can be reversed when specific activities in the watershed result in seasonal contamination during times of low precipitation. McDonald *et al.* (2008) examined surface water FC concentration in a protected wilderness area in Scotland. Contrary to expectations, they found significantly more contamination in summer than winter. They suggested that greater numbers of visitors coupled with low summer flows would have contributed to greater FC concentration.

At still greater temporal scales, significant positive correlation between annual precipitation and FC concentration have been observed in the Gulf of Mexico. In Florida, Lipp *et al.* (2001a) observed an association between greater mean annual precipitation and correspondingly higher FC concentration in the Charlotte Harbour estuary. Years with greater total precipitation were thought to experience increased soil saturation, which would have increased runoff and transport of fecal waste from failing septic systems into the estuary. Similar processes in the Pearl River watershed were thought to have increased FC loading into the Mississippi Sound (Chigbu *et al.,* 2004).

Studies have investigated the capacity of hydro-meteorological parameters to be used as predictors of the presence and variability of surface water fecal contamination, but have been met with little success. Schaffter and Parriaux (2002) and Schaffter *et al.* (2004) examined the presence of four different waterborne pathogens in relation to hydro-meteorological variability within a mountainous watershed in Switzerland. Temperature and rainfall were significant predictors, however, the degree to which they related to pathogen presence varied between seasons to such an extent that no general conclusions could be drawn.

Wilkes *et al.* (2009) examined FC concentration variability in relation to hydrological variables throughout the South Nation watershed in Ontario. They also found the strength and direction of relationships to be variable. Positive associations between FC concentration and rainfall were strongest in spring and summer, but inconsistent among seasons and sites. Associations between FC concentration and river discharge were positive in fall and winter, but negative in spring and summer. As a result, Wilkes *et al.* (2009) were unable to identify a consistently strong hydrological indicator of contamination within the watershed. The strength and direction of relationships between FC concentration and hydrological variability were broadly dependent on seasonal characteristics, the type of coliform sampled, sample site disposition (e.g. stream order), and differences in specific hydrological loading/transport processes. This list illustrates the challenge of modeling FC concentration variability in relation to hydro-meteorological factors, as confounding variables introduce a high level of inconsistency between study period and location.

The influence of hydrological variability on FC concentration has been assessed by comparison of contamination levels during “non-event” base-flow conditions and “event” heavy rainfall and high-flow conditions. Kistemann *et al.* (2002) compared microbial loading into source water reservoirs in Germany during these two conditions. Bacterial loads increased to maximum levels during events that generated high surface runoff and were significantly greater than during non-event conditions. High bacteria and parasite loads indicated the release of fecal contaminants from overwhelmed sewage systems within the watershed.

Kay *et al.,* (2008) performed a similar assessment on 15 catchment-based studies in the UK from 1995 to 2005. FC concentration was significantly higher during high (rainfall-enhanced) flow compared to low (base) flow. This was thought to be due to increased surface runoff, entrainment of streambed sources, and reduced die off and sedimentation of FC. High-flow FC concentration was greater in summer than winter, ostensibly due to greater fecal inputs and infrequent flushing of contaminants under drier conditions. The same relationship was seen in an urbanized catchment in the Adelaide Hills, South Australia, however, there was no evidence that prior rainfall or concurrent river discharge levels could be used to estimate FC concentration during such events (Signor *et al.,* 2005).

There is significant evidence for the influence of hydro-meteorological and land-use factors on surface water fecal contamination. But, like the Vancouver Canucks hockey team record, results are consistently variable. Despite this, the potential for more intense precipitation to increase surface water fecal contamination has been well substantiated by observed increases in FC loading during times of high rainfall-induced runoff. Fecal contamination tends to be greater during such events in watersheds impacted by urban development and agriculture. From these studies it can be concluded that the combined influence of surface runoff and anthropogenic land-use act in a synergistic fashion to increase fecal contamination levels in surface water.

1.5 Climate change and surface water fecal contamination

Relationships between hydro-meteorological parameters that influence surface runoff, source water contamination, and disease outbreaks suggest that climate change can alter the risk of waterborne disease. These concerns have been voiced by the World Health Organisation (WHO), the Inter-governmental Panel on Climate Change (IPCC), and the National Research Council (NRC) (McMichael *et al.,* 2004; Confalonieri *et al.,* 2007; Lemmen, 2008). The IPCC has classified the probability of source water degradation and increased cases of waterborne infections as *very likely*, a term indicating 90% confidence. Anticipated increases in heavy precipitation and flooding present a greater opportunity for pathogen persistence in the environment and exposure to hosts (Patz *et al.,* 2008). British Columbia (BC) is projected to experience temperature increases of 1.7^0 to 4.0^0C by 2080 and precipitation increases of 20-30% by the year 2100 (Bates *et al.,* 2008; Murdock and Spittlehouse, 2011).

Shifting river hydrographs in BC illustrate the influence of warmer springs, drier and hotter summers, and warmer and wetter winters on watershed runoff regime. From the early 1970's through to the mid 1990's the Upper Similkameen River hydrograph showed typical changes occurring to annual trends in river discharge for the interior, snowmelt-dominant, region of BC (Fraser 2002). River discharge levels began to increase earlier in the year due to early snowmelt, which caused earlier peak discharge, followed by a more rapid decline in discharge during summer. The combination of an early decline in discharge and reduced summer precipitation has produced prolonged and extreme low flows. In the fall season, warmer temperatures have increased rainfall and elevated river discharge (Fraser 2002). This is indicative of changes to watershed runoff regimes in BC, which have generally experienced an increase in annual variability.

Shifting river hydrographs and an increase in the frequency and severity of heavy rainfall events will likely influence FC concentration variability in surface water. British Columbia is projected to experience less precipitation during the summer and more precipitation during the winter (Schnorbus *et al.,* 2011). Greater precipitation over contracted periods of time will increase soil saturation, reduce the area of air-water interfaces, and will ultimately lead to a greater frequency of macro-pore and overland flow events. This is likely to facilitate a more rapid transport of fecal pathogens through channels of preferential flow (Ferguson, 2003; Boxall *et al.,* 2009). High river discharge may further increase pathogen concentrations by re-suspending the upper layers of stream and river sediments, containing adsorbed pathogens. Pathogen transport may also increase in summer due to greater hydrophobicity of soil surfaces, resulting from higher temperatures and reduced precipitation, which will reduce infiltration and amplify surface runoff during intense summer rainfall events. Furthermore, projected reductions in total summer rainfall reduces river discharge volumes and dilution of contaminants (Boxall *et al.,* 2009). These factors may lead to changes to the timing and magnitude of risk to drinking water posed by source water fecal contamination. Identifying the presence and consistency of relationships between these factors and surface water fecal contamination is required to assess this risk.

1.6 Thesis objectives and structure

This thesis examines the impacts of land-use and hydro-meteorological variability on surface water fecal contamination in relation to projected climate change. The main aim is to assess the capacity for changes in land-use and climate to influence surface water fecal contamination.

Chapter 1, the introduction to this thesis, provided the motivation for this work by reviewing the factors that influence fecal contamination of source water and waterborne disease. It considered the factors that influence fecal contaminant presence, mobilization, and transport into surface water. These relationships are considered in light of current and predicted hydro-meteorological variability resulting from climate change. The need for further examination of these associations over spatial and temporal scales pertinent to the influence of climate change are identified.

Chapter 2 provides information on the study region, the type of data that were available and collected, and the sources of data that are common to the thesis as a whole. Details regarding common materials used throughout the thesis are presented in a single separate chapter in order to avoid repetition and increase the fluency of subsequent chapters.

Chapter 3, entitled, *The impact of land-use on surface water fecal contamination*, examines the association between land-use composition and surface water fecal contamination. Fecal contaminants are generated by land-use activities and their transport in the watershed is modified by land-use influences on the landscape (Tate *et al.,* 2004;

Arnone and Walling, 2007; Coffey *et al.,* 2010). Land-use is, therefore, likely to be related to surface water fecal contamination among watersheds. This is examined by quantifying the relationship between land-use and FC concentration. The strength of this relationship helps to establish the risk associated with changes to land-use composition in watersheds. This chapter examines these relationships by identifying land types positively associated with FC concentration and using these land types to examine their influence on FC parameters crucial to the maintenance of safe source water. The extent of the relationship observed between land-use and FC parameters is used to consider the risk of greater surface water fecal contamination associated with anthropogenic impacts.

Chapter 4, entitled, *The influence of hydro-climatic regime on seasonal variability of surface water fecal contamination*, examines the association between seasonal hydro-meteorological and FC concentration variability. Highly variable and weak relationships observed between seasonal FC concentration and hydro-meteorological variability (Cha *et al.,* 2010; Parker *et al.,* 2010; Sigua *et al.,* 2010) obscure estimation of the impact of shifting runoff regimes on fecal contamination (Fraser, 2002; Schnorbus *et al.*, 2011; WDWF, 2011) on seasonal patterns of fecal contamination. This chapter aims to address this by: 1) examining FC concentration variability in relation to hydro-meteorological variability, and investigating how this association varies among watersheds with different climate regimes; and 2) examining the hydro-meteorological characteristics associated with seasonal FC concentration variability. This chapter explores evidence for general basic relationships that characterize hydro-meteorological influences on seasonal FC concentration variability under different climate regimes. These relationships are utilised to consider the influence of climate change on seasonal patterns of fecal contamination and the risk this presents to water treatment.

Chapter 5, entitled, *The influence of inter-annual hydro-meteorological variability on surface water fecal contamination*, examines the association between inter-annual hydro-meteorological and FC concentration variability. Climate change is anticipated to increase the total volume and variability of precipitation in BC (Bates *et al.,* 2008). Given that heavy and prolonged precipitation increases runoff, which increases the transport of fecal contaminants into surface water (Dorner *et al.,* 2006, King and Monis, 2007; Boxall *et al.,* 2009), increases in precipitation have the potential to increase the risk of source water exposure to fecal contaminants (McMichael *et al.*, 2004; Confalonieri *et al.*, 2007; Lemmen *et al.,* 2008). This potential is investigated using inter-annual hydro-meteorological variability in BC, which is relatively high due to the temperate climate and El Niño and Pacific Decadal Oscillation climate patterns (Manuta and Hare, 2002; Lorenzo *et al.,* 2010). This chapter aims to quantify the extent to which mean seasonal and annual FC concentrations are related to hydro-meteorological variability. The associations observed are used to consider the risk of increased precipitation on surface water fecal contamination.

Chapter 6, the last, is entitled *Synthesis and interpretation of results*. It provides a synthesis of the conclusions from each part of the study and applies them to the central aim of the thesis, which is to better anticipate the influence of climate change on surface source water fecal contamination in BC. Original contributions made by this thesis are considered in relation to previous work conducted by others, and are applied to areas of existing uncertainty regarding factors influencing surface water fecal contamination. The limitations of this research are discussed and remaining areas of uncertainty requiring further research are identified.

Chapter 2 Study region and data collection

2.1 Study region

This study utilized data from watersheds within the province of BC, Canada. The province covers an area of 944,735 km^2, 75% of which is mountainous. It extends from the pacific coastline in the west up to the Rocky Mountain range in the east and between 49^0 and 60^0 latitude N. Hydro-meteorological characteristics in the province change in relation to distance from the ocean and physiographic terrain of the interior. Coastal BC has a mild and wet oceanic climate due to the Kuroshio Current that transports warm tropical water into the northeast Pacific Ocean. Precipitation quickly decreases towards the interior due to the rain-shadow cast on the leeward side of successive mountain ranges and temperature ranges increase in the absence of the ocean to moderate seasonal fluctuations in temperature (Shabbar *et al.,* 1997). Dense climax forests of western hemlock and red-cedar characterize the relatively mild and very moist coastal region of the West Coast. Climax vegetation transitions into interior Douglas fir and Engelmann spruce with decreasing moisture towards the interior. Dry leeward valleys in the southern interior are covered by native grass shrub-grasslands (BC MoE, 2011a).

Figure 2.1.1 illustrates the contrast between seasonal rainfall and river discharge in watersheds with different hydro-climatic regimes in the study region (as described in Shrestha *et al.*, 2011). Annual temperature variability and mean annual trends in rainfall and river discharge are shown for the rainfall-dominant (RD) Sooke River watershed on the southern end of Vancouver Island and for the snowmelt-dominant (SD) Mission Creek watershed, located near Kelowna in the southern interior of BC. Temperature variability was greater in Kelowna than Sooke (Fig. 2.1.1). At both locations precipitation was greater in fall and winter than spring and summer. In Kelowna, mean winter temperatures below zero resulted in snowfall in fall and winter and rainfall in spring and summer. Mean total annual precipitation was low (298mm and 1018mm of rainfall and snowfall, respectively). Sooke had mean winter temperatures above zero and received rainfall throughout the year. Mean total annual precipitation was high (1413mm and 792mm of rainfall and snowfall, respectively). In Kelowna, river discharge increased during spring due to snowmelt, decreased rapidly in early summer, and remained low during fall and winter. In Sooke, river discharge increased in late fall due to higher rainfall, peaked in January, and returned to lower flows in spring and summer (Fig. 2.1.1).

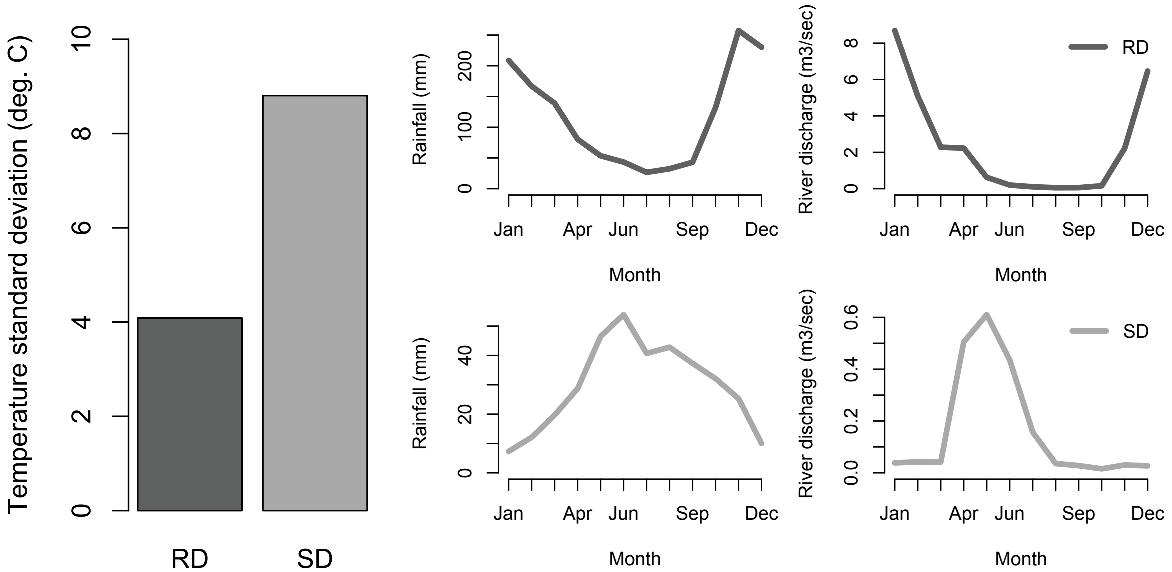

Figure 2.1.1 A comparison of the annual temperature variability, mean monthly rainfall, and mean monthly river discharge in the rainfall-dominant (RD) Sooke watershed, Vancouver Island (dark shading), and the snowmelt-dominant (SD) Mission Creek watershed, Kelowna (light shading).

2.2 Data collection

2.2.1 Fecal coliform

Measurements of FC concentration (CFU $100ml^{-1}$) for surface water sites (not necessarily source water) within BC were obtained from the Environment Canada Water Quality Monitoring Program (ECWQMP) and are available online at http://waterquality.ec.gc.ca/waterqualityweb/searchtext.aspx. Fecal coliform was the most common measure of fecal contamination and was used whenever possible. For watersheds where FC concentration was not measured *Escherichia coli* concentration was used. *E. coli* data were considered valid for comparison with FC data as concentrations were highly equivalent at sites where both were enumerated. Furthermore, BC raw water quality guidelines are identical for FC and *E. coli* (Warrington, 2001a). Data were obtained for 43 sites across BC that were considered appropriate for this study, according to a minimum frequency of two data points per month. Figure 2.1.1 shows the location and area of watersheds (as delineated in the Freshwater Assessment Atlas obtained from GeoBC, see Appendix A) utilized for this study.

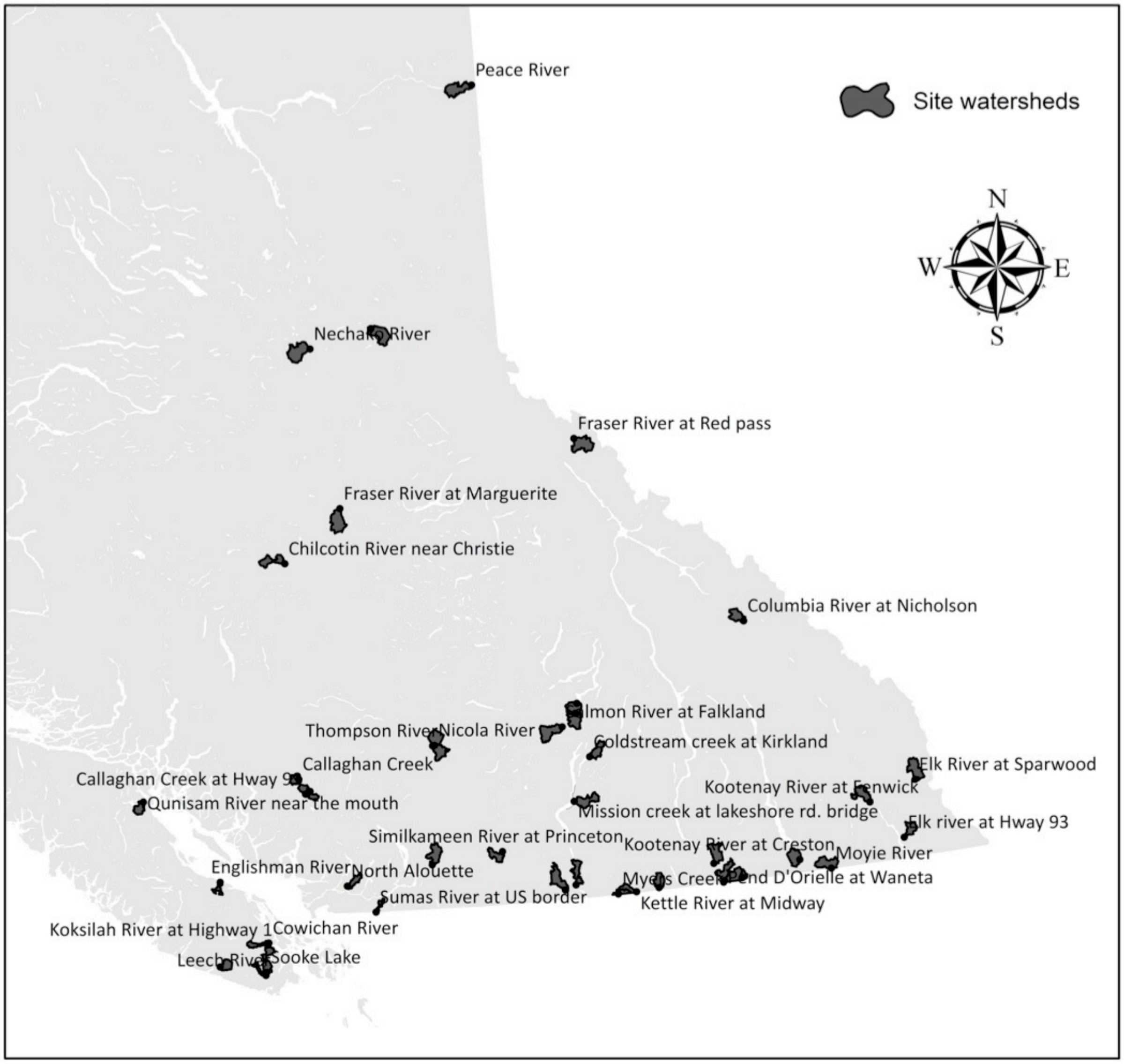

Figure 2.2.1 Map of sample sites and their upstream watershed within British Columbia, Canada.

2.2.2 Land use

Land use data was obtained from the BC government online resource for Geographical Information Science (GIS), GeoBC, which is available online at http://geobc.gov.bc.ca/. The area of land upstream of the sample site was marked out using catchment boundaries provided by the Freshwater Assessment Atlas (Appendix A) on ArcGIS 9.3 software (ESRI, 2008). These catchments were considered to be the most appropriate scale at which to measure land-use composition capable of influencing downstream FC concentration. Although the area upstream of a sample location that influences FC concentration is not well defined in the literature, land-use has been found to be significantly associated with FC concentration when characterized at the 5 km and 10 km spatial scales, but not at finer resolution (at the 1 km scale) or the watershed scale (Hurley, 2012). The sample sub-watersheds exceed the land area shown to be necessary to identify land-use influences on FC concentration but, in most cases, were much smaller than the total watershed area (range of sample watersheds = 19,000 to 258,000 km^2). Variability in sample watershed area is principally due to higher-order rivers and sites located at the confluence of tributaries having larger catchment areas upstream of the sample location (Fig. 2.2.2 and Table 2.2.1). The percentage cover of up to 17 different land-use types within sample watersheds were calculated from the area as marked by baseline thematic mapping obtained from GeoBC (Appendix A).

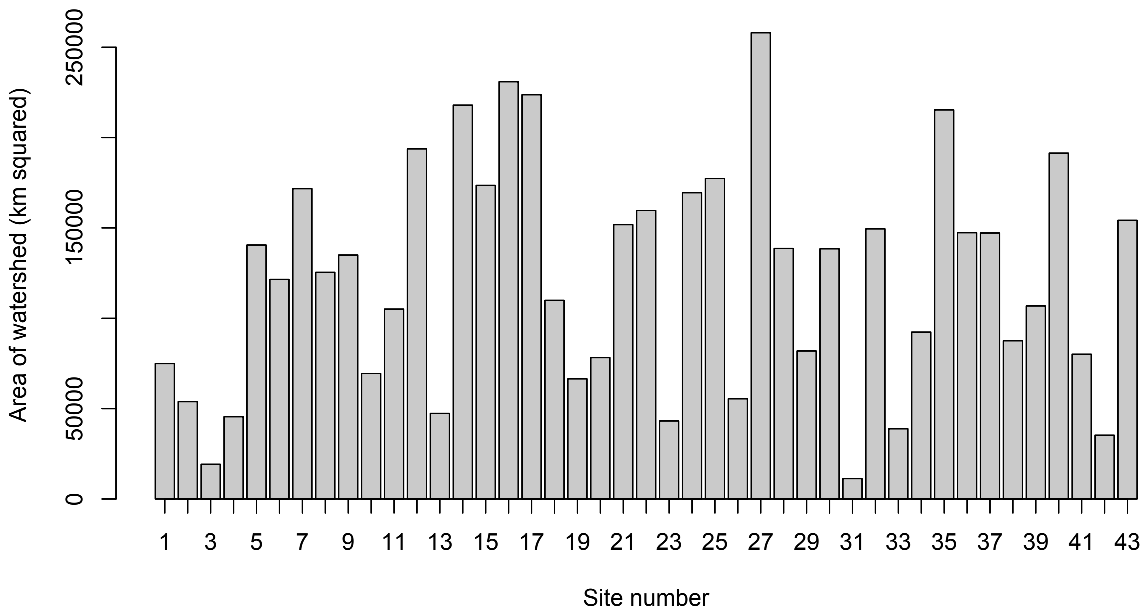

Figure 2.2.2 The total area of each sample watershed (km^2).

Table 2.2.1 Watershed and site characteristics, including hydrograph type (SD = snowmelt-dominant, RSI = rainfall and snowmelt influenced, and RD = rainfall-dominant) and their mean, standard error and range of fecal coliform concentration.

Site name	Site no.	Sample n	Longitude	Latitude	Watershed area (000's km2)	Mean elevation (m)	Hydrograph type	Agricultural land (%)	Fecal coliform: Mean, SE, and range (CFU/100ml)
Chilcotin River near Christie	5	48	-123.26	52.07	140.54	875.22	SD	5.67	2.33±1.83 (1-80)
Coldstream creek at Kirkland	6	64	-119.22	50.22	121.51	1039.84	SD	18.45	288.81±41.82 (34-1700)
Columbia River at Nicholson	8	39	-116.91	51.24	125.44	1103.02	SD	0.26	2.01±1.2 (1-32)
Columbia River at Waneta	9	334	-117.60	49.02	135.01	855.07	SD	0.81	4.84±1.69 (1-290)
Elk river at Hway 93	11	126	-115.17	49.18	105.10	1257.16	SD	1.17	3.18±1.5 (1-151)
Elk River at Sparwood	12	87	-114.90	49.66	193.73	1470.68	SD	5.71	1.87±1.4 (1-95)
Fraser River at Hansard	14	85	-121.85	54.08	217.96	671.83	SD	2.54	4.05±1.36 (1-81)
Fraser River at Hope	15	164	-121.45	49.39	173.55	844.44	SD	0.00	16.37±10.75 (1-1600)
Fraser River at Marguerite	16	124	-122.44	52.53	230.90	783.95	SD	4.95	39.48±49.88 (1-5400)
Fraser River at Red pass	17	147	-119.01	52.99	223.70	1700.82	SD	0.00	1.14±0.41 (1-59)
Kettle River at Carson	18	162	-118.47	49.02	109.94	826.81	SD	11.01	4.81±1.58 (1-128)
Kettle River at Midway	19	172	-118.78	49.00	66.48	788.65	SD	23.65	7.84±3.22 (1-480)
Kootenay River at Creston	21	163	-116.58	49.12	151.82	1132.61	SD	19.21	3.12±1.84 (1-200)
Kootenay River at Fenwick	22	134	-115.55	49.53	159.64	873.65	SD	10.22	3.18±1.06 (1-75)
Mission creek at lakeshore rd. bridge	24	42	-119.49	49.84	169.48	991.88	SD	16.12	55.71±39.56 (4-1600)
Moyie River	25	32	-116.18	49.00	177.36	1334.91	SD	1.87	4.25±1.51 (1-36)
Myers Creek	26	120	-119.02	49.00	55.45	868.32	SD	6.33	26.28±7.44 (1-430)
Nechako River	27	170	-122.77	53.93	258.00	661.74	SD	10.57	4.65±2.93 (1-400)
Nicola River	28	58	-121.32	50.43	138.64	1073.35	SD	0.54	9.55±4.83 (1-170)
Okanagan River at Oliver	30	171	-119.57	49.11	138.45	540.71	SD	22.10	6.4±1.27 (1-98)
Peace River	31	135	-120.06	56.13	11.30	526.33	SD	44.82	3.55±4.15 (1-330)
Salmon River at Falkland	35	592	-119.56	50.50	215.30	1025.83	SD	17.24	66.18±2.31 (4-205)
Salmon river at Salmon Arm	36	2557	-119.33	50.69	147.35	1128.82	SD	14.98	71.37±1.23 (4-300)
Salmon River at Silver Creek	37	60	-119.36	50.61	147.19	1078.06	SD	14.00	72.13±25.12 (3-1000)
Similkameen River at Princeton	39	186	-120.50	49.46	106.82	925.98	SD	2.63	2.23±1.69 (1-284)
Similkameen River at US boarder	40	158	-119.71	49.08	191.41	960.52	SD	17.28	4.26±1.93 (1-200)
Thompson River	43	154	-121.34	50.42	154.23	838.86	SD	3.35	2.59±1.25 (1-150)
Cowichan River	10	199	-123.66	48.77	69.44	192.10	RD	0.49	9.91±5.65 (1-700)
Englishman River	13	56	-124.29	49.32	47.36	195.47	RD	0.00	18.65±7.18 (1-330)
Koksilah River at Highway 1	20	199	-123.67	48.76	78.25	196.92	RD	22.84	19.33±24.62 (1-4600)
Leech River	23	64	-123.72	48.49	43.17	421.23	RD	0.00	0±0.41 (0-23)
North Alouette	29	74	-122.60	49.24	81.90	644.00	RD	0.00	9.17±5.67 (1-380)
Qunisam River near the mouth	34	42	-125.30	50.03	92.36	169.68	RD	0.00	15.31±3.28 (1-85)
San Juan River	38	60	-124.31	48.58	87.56	436.35	RD	0.00	5.54±2.94 (1-157)
Sooke Lake	41	222	-123.70	48.52	80.12	374.97	RD	0.00	0±0.18 (0-20)
Sumas River at US border	42	55	-122.23	49.00	35.31	231.67	RD	52.62	305.38±128.34 (20-6100)
Callaghan Creek	1	44	-123.18	50.19	74.94	1615.42	RSI	0.00	1.13±0.16 (1-7)
Callaghan Creek at Hway 99	2	70	-123.10	50.06	53.88	1126.75	RSI	0.00	1.36±1.86 (1-130)
Cheakamus River below sewage plant	3	75	-123.10	50.06	19.23	896.80	RSI	0.00	4.54±31.67 (1-2200)
Cheakamus River on lake road	4	42	-123.04	50.08	45.53	1113.75	RSI	0.00	1.15±0.34 (1-15)
Columbia River at Birchbank	7	186	-117.72	49.18	171.72	893.03	RSI	0.73	1.58±1.16 (1-170)
Pend D'Orielle at Waneta	32	44	-117.37	49.02	149.47	1030.56	RSI	3.82	1.22±0.51 (1-23)
Pend D’Orielle at US boarder	33	82	-117.62	49.00	38.85	998.95	RSI	0.00	1.09±0.04 (1-3)

2.2.3 Hydro-meteorological data

Daily mean data for temperature, rainfall, and river discharge were obtained from the nearest available meteorological and hydrometric stations. Average daily temperature and rainfall was downloaded from Canada’s National Weather Data Archive (available online at www.climate.weatheroffice.gc.ca), and river discharge (the term river discharge is used throughout, although a small proportion of water systems would be classified as streams) data from Canada's Water Survey (available online at www.ec.gc.ca). Three-day cumulative rainfall prior to day of sampling was utilized as it has been shown to correlate more strongly with FC concentration variability than mean rainfall on day of sampling, likely due to three days being more representative of rainfall variability and the lag associated with FC transport (Wilkes *et al.*, 2009).

These same data sets were utilized for three separate, but related, studies on the response of FC concentration to land use and climate variability, detailed in the following chapters.

Chapter 3 The impact of land-use on surface water fecal contamination

Abstract

Source water fecal contamination results in millions of waterborne infections each year. The potential for surface water to become contaminated with pathogens increases in relation to the amount of fecal waste produced in the surrounding watershed. Minimising fecal contamination of source water is critical to the production of safe clean drinking water. This study identifies the associations between different land-use types and fecal contamination variability in surface water. Fecal coliform data were obtained for 43 sites within BC, Canada, and their upstream watershed land-use composition was calculated. Land-use types that were positively associated with FC concentration was identified using Spearman's Rank and the relationship between site FC concentration and land-use composition assessed using simple linear regression. Fecal coliform concentration in surface water significantly increased due to the contribution of diffuse fecal contamination from anthropogenic activity within watersheds. Agricultural land had the strongest positive correlation with mean FC concentration (Spearman's rank: $\rho = 0.46$, $p = 0.001$). High FC concentrations occurred in watersheds characterized by having more than 12.5% agricultural and greater than 1.6% urban land (mean FC concentration of these five sites = 135 CFU $100ml^{-1}$). The proportion of agricultural land in the upstream watershed was positively related to surface water FC concentration and variance ($r^2 = 0.90$, $p = <0.001$; $r^2 = 0.61$, $p = <0.001$, respectively), and also increased the frequency of samples that violated the BC raw water quality guideline for FC concentration (100 CFU

100ml^{-1}). Additional factors, such as sewage treatment discharge, low dilution in smaller streams, and higher temperatures were associated with higher baseline FC concentration in certain watersheds. Variability in FC concentration was also observed between watersheds that did not show evidence of land-use impacts on surface water fecal contamination, ostensibly due to point-source contamination. These watersheds highlight the need to quantify factors known to influence FC variability that were not considered in this study, such as the presence of point-source contamination and watershed geological, riparian, and management characteristics. This study demonstrated that diffuse fecal contaminants generated by land-use activities present a threat to surface source water quality, especially during times of surface runoff mediated transport. This stresses the importance of source water protection, especially in watersheds with urban and agricultural land-use, in order to minimize the risk of surface water exposure to fecal contamination.

3.1 Introduction

Waterborne pathogens present a critical risk to the production and provision of safe drinking water. Pathogen contamination of surface source water originates in land-use activities that generate and discharge fecal contaminants, either directly, through point sources, or indirectly, as diffuse sources. Recent success in the control and reduction of point source contamination has shifted current research efforts towards managing the influence of diffuse sources (Kloot, 2006). Diffuse sources include manure applied to land, livestock waste, recreational activity, and wildlife feces (Tyrrel and Quinton, 2003; Meays *et al.,* 2006b). Locating and quantifying diffuse sources is challenging because of the large areas over which they originate and their high temporal variability. Land-use impacts and mitigation efforts, such as source water protection, strongly influence the risk that diffuse contamination presents to surface source water quality (Charron *et al.,* 2004).

Land-use activities and modifications made to the landscape influence the quantity of fecal contamination generated and transported into surface water. Anthropogenic land-use impacts, such as urban and agricultural development, are sources of diffuse fecal contaminants (Environment Canada, 2001; Coffey *et al.,* 2010). Urban areas contain high concentrations of fecal waste in sewer systems that are vulnerable to overflow and leaching (Arnone and Walling, 2007). Hydraulic modifications that increase surface runoff in urban areas, such as gutters, storm sewers, and pavement, increase the speed and amount of fecal contaminant transported into surface water. Livestock produce large quantities of fecal waste. The combined manure production of cows, pigs, and poultry in Canada can amount to over 177 billion kilograms per year

(Unger, 2008). Manure is spread onto fields as a source of fertilizer, where it is prone to leach into nearby watercourses. As a result, fecal contamination in surface water is significantly higher in watersheds with agriculture, especially with livestock production, than protected watersheds in which these activities are restricted (Sigua *et al.,* 2010; Walters *et al.,* 2010).

The impact of land-use on surface water quality can be ameliorated or exasperated by improved management practices within a watershed. Tate *et al.* (2004) have demonstrated the efficacy of maintaining riparian vegetation as a barrier to arrest fecal contamination, which can be aided by denying livestock direct access to streams and rivers. Conversely, the removal of vegetation associated with logging and some forms of agriculture can significantly reduce infiltration, which amplifies runoff, turbidity, and pathogen loading into downstream source water (Atwill *et al.,* 2002). Survival and transport of fecal contamination is further influenced by abiotic factors within the watershed. Survival tends to be enhanced by low temperatures and UV, moderate pH, and high nutrient levels, while transport is facilitated by intact and well structured soils with many macropores and a large grain size, frequent and high intensity rainfall, and high river discharge (Ferguson *et al.,* 2003a). These factors can generate high variability in surface water fecal contamination among watersheds with very similar land-use composition.

Impacted land can increase the risk of drinking water contamination and the transmission of waterborne pathogens. Source water FC concentration increases rapidly during rainfall and snowmelt events within watersheds influenced by agricultural and urban development (Kay *et al.,* 2008; Sigua *et al.,* 2010). By contrast, the response is much lower in pristine or forested watersheds (Kistermann *et al.,* 2002). Turbidity and fecal pathogen concentration in raw drinking source water tend to be positively correlated (Gauthier *et al.,* 2003). Organic matter, including fecal contaminants, reduce the efficiency of water disinfection processes and consume the chlorine residual designed to eliminate microbial growth and persistence in water distribution systems (Lemmen *et al.,* 2008). These conditions increase the risk of human exposure to waterborne pathogens in drinking water.

It is important to examine the influence of different land-uses on surface water fecal contamination in order to identify the risk associated with changes in land-use composition. Increasing land-use pressures from intensification of agriculture and urban development and the increasing intensity of hydro-meteorological events pose a potential threat to source water quality. The extent to which land-use composition influences downstream fecal contamination is a crucial factor to consider in mitigating the future risk of waterborne disease associated with projected degradation of source water quality (Delpla *et al.,* 2009).

3.1.1 Objectives

This study aims to identify the association between land-use composition and surface water fecal contamination. The objectives are to: 1) identify land-use types positively associated with FC concentration and 2) examine the association between land-use and fecal contamination in relation to the maintenance of safe source water. It was hypothesized that land-use types with anthropogenic impact, i.e. greater livestock and human populations (termed “impacted land”), would be positively associated with increased FC concentrations. Mean FC concentration was expected to be variable in relation to the proportion of impacted land among watersheds, however, due to additional factors, beyond land-use composition, that influence surface water fecal contamination, such as vegetation, topography, and management activities.

3.2 Data analysis and statistics

Land-use, climate, and FC data from all the sites identified in chapter 2 were utilized in this study. Land-use that contributed to FC contamination was determined by examining the strength of correlation between each land-use type and FC concentration. Spearman's Rank correlation method was used as the data were non-parametric. A regression-tree model was used to indicate the proportion of land-use types that most strongly determined FC concentration variability between watersheds. A regression tree model uses binary recursive partitioning, whereby the data were successively split along coordinate axes of each land-use type so that at any node, the split was chosen that maximally distinguished FC concentration in the left and right branches. A generalized linear model (GLM) using different land-use types as predictors of watershed mean FC concentration was fit to the data in order to determine the significance and explanatory power of each land-use type while accounting for interactions.

Fecal coliform concentration and variance were examined as a function of the proportion of impacted land within watersheds. Variance was calculated from monthly mean values of the entire available dataset for each site. Cluster analysis was used in an exploratory way to identify groups of sites that showed a similar response in mean FC concentration to the proportion of agricultural land in the upstream watershed. Simple linear regression with 95% confidence intervals was used to determine what proportion of impacted land is associated with mean FC concentration above the BC raw water quality guideline of 100 CFU $100ml^{-1}$ (Warrington, 2001). Cumulative density frequency plots were used to determine the frequency with which FC samples exceeded the BC raw water quality guideline at each site. The proportion of samples above the raw water quality guideline was examined in relation to impacted land within the watershed.

The geometric mean (calculated as $GM = 10^{\chi}$, where χ = mean of $\log_{10}$-transformed values) was used to measure central tendency of FC concentrations, which follow a $\log_{10}$ normal probability density function in surface water (Wilkes *et al.,* 2009). All data handling, graphics, and statistical analysis were performed with the statistical software R (R Development Core Team, 2009).

3.3 Results

3.3.1 Land-use type and fecal coliform concentrations

Agriculture and young forest land-types both had a significant positive correlation with mean FC concentration (Spearman's rank = 0.46 and 0.33, p=0.001 and 0.02 respectively). Other land-use types that were positively associated with FC concentration were characterised by anthropogenic impacts, and included urban, burnt, and recreational land. Significant negative correlations were observed between FC concentration and high elevation land-use types, namely sub-alpine, alpine, and glacial. Other land types negatively associated with FC concentration were relatively less disturbed areas covered by old forest, barren-land, and wetlands (Fig. 3.3.1) (percentage cover of each land-use type for each watershed is given in Appendix A).

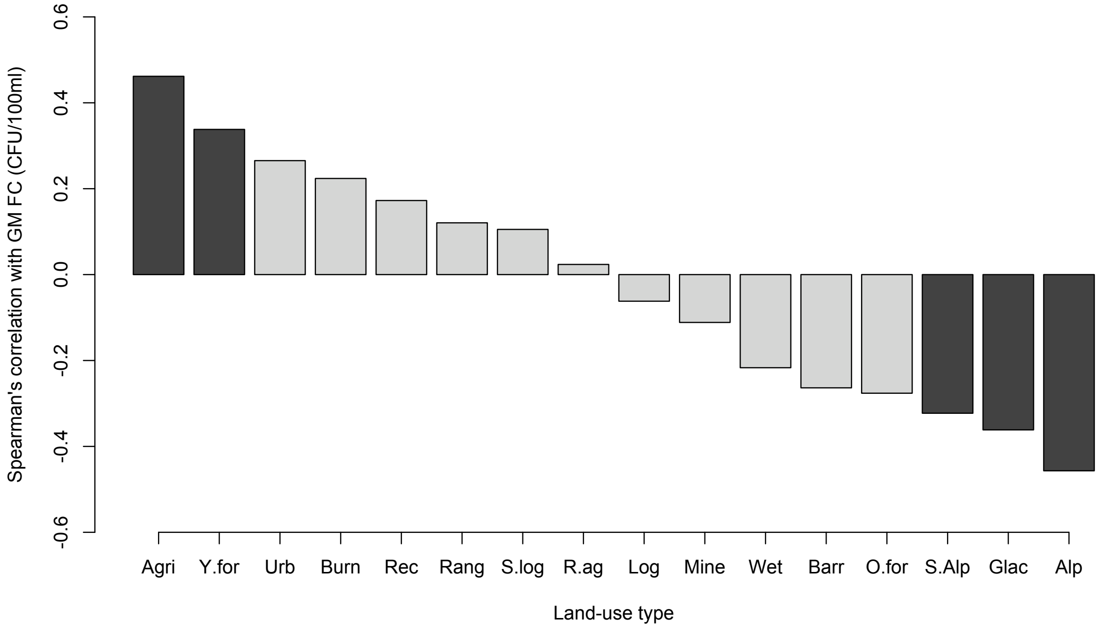

Figure 3.3.1 The Spearman's Rank correlation coefficient of the percentage of each land-use type with the geometric mean fecal coliform concentration (GM FC) of each site (Agri = Agriculture; Y. for = Young forest; Urb = Urban; Burn = Burned; Rec = Recreational; Rang = Range land; S. log = Selectively logged; R. ag = Residential agriculture; Log = Logged; Mine = Mining; Wet = Wetlands; Barr = Barren; O. for = Old forest; S. Alp = Sub Alpine; Glac = Glacier; Alp = Alpine). Darker bars show a significant Spearman's rank correlation coefficient ($p<0.05$).

Agricultural land explained the greatest amount of FC concentration variability among watersheds. A regression tree model, which included all the land-use types that were positively correlated with FC, determined that watersheds with greater FC concentrations were best differentiated from those with lower FC concentrations by having more than 12.5% agricultural land. Urban land further differentiated sites with watersheds that had more than 12.5% agricultural and 1.6% urban land. These sites had the greatest FC concentrations (mean FC concentration = 135 CFU $100ml^{-1}$). Those with more than 13% agricultural but less than 1.6% urban land had intermediate FC concentrations (mean FC concentration = 32.6 CFU $100ml^{-1}$) and those with less than

13% agricultural land the lowest FC concentrations (mean FC concentration = 6.5 CFU $100ml^{-1}$) (Fig 3.3.2).

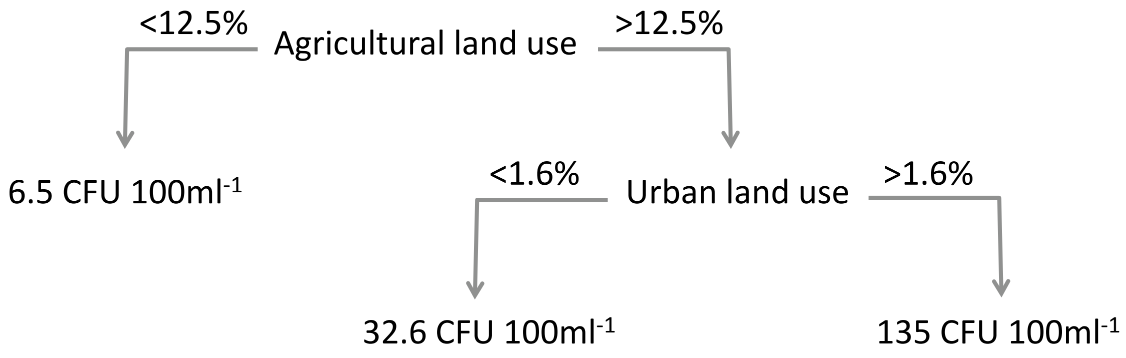

Figure 3.3.2 A regression tree model, using binary recursive partitioning, showing land-use type and percentage cover that maximally differentiated mean fecal coliform concentration in the left and right branches.

3.3.2 Land-use impact and fecal coliform concentrations

Agriculture was the only remaining significant parameter ($t = 4.79$, $p = <0.001$) in a GLM, after stepwise deletion of non-significant land-use parameters, used to identify significant explanatory land-use variables of FC concentration variability among watersheds. This identified agricultural land as the best indicator of the extent of impacted land.

Fecal coliform concentration was strongly related to the proportion of upstream agricultural land for many of the watershed sampling sites (Fig. 3.3.3). Sites were divided into groups that appeared to demonstrate different responses in FC concentration in relation to agricultural land. Group 1 sites ($n = 20$) demonstrated a relationship in which the regression line passed close to the origin, indicating that agricultural land was the principle source of fecal contamination. Group 2 sites ($n = 12$) had a similar slope but intercepted the y-axis just above 10 CFU 100ml^{-1}, and thus have a higher baseline FC concentration than Group 1. The remaining sites that did not show any relationship between land-use and FC concentration were termed “anomalies” (n = 11). Group 1 and 2 sites showed significant log linear relationships between the proportion of upstream agricultural land and FC concentration ($r^2 = 0.90$, $p = <0.001$ and $r^2 = 0.84$, $p = <0.001$, respectively). Group 1 sites predicted FC concentration to exceed the criteria of 100 CFU 100ml^{-1} in watersheds with more than 46% agricultural land (95% CI = 41-53%). The regression line for Group 2 sites predicted this to be lower, at 19% (95% CI = 16-25%), due to the higher baseline FC concentration (Fig. 3.3.3).

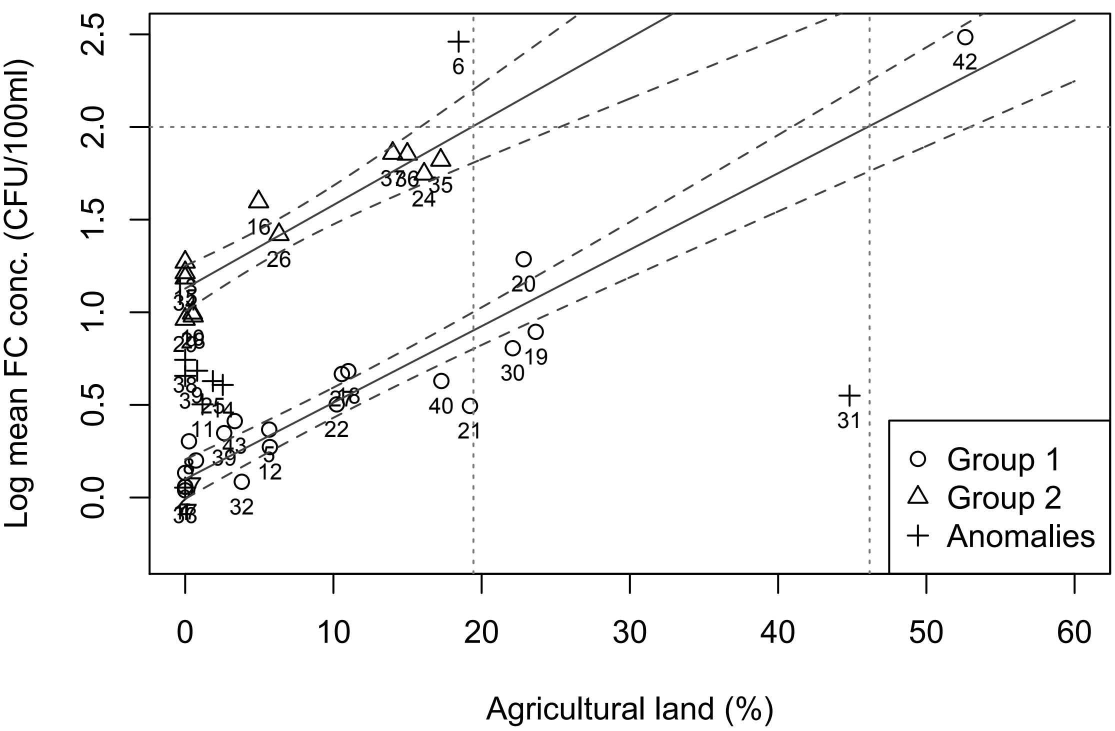

Figure 3.3.3 Log_{10} mean fecal coliform concentrations (FC conc.) plotted against the percentage of agricultural land within the upstream watershed (slope shown by solid lines and 95% CI by dashed lines on either side). The dotted horizontal line shows the British Columbia raw drinking source water quality criteria threshold of 100 CFU 100ml^{-1} ($\log_{10}$ of 100 = 2) and the dotted vertical lines show where the Group1 and Group 2 regression lines intersect the guideline threshold.

Fecal coliform variance increased in relation to the proportion of increasing upstream agricultural land (Fig. 3.3.4). A significant positive relationship was observed between FC variance and land-use among Group 1 sites, whereas this was not the case among Group 2 sites ($r^2 = 0.74$, $p = <0.001$; $r^2 = 0.18$, $p = 0.121$, respectively).

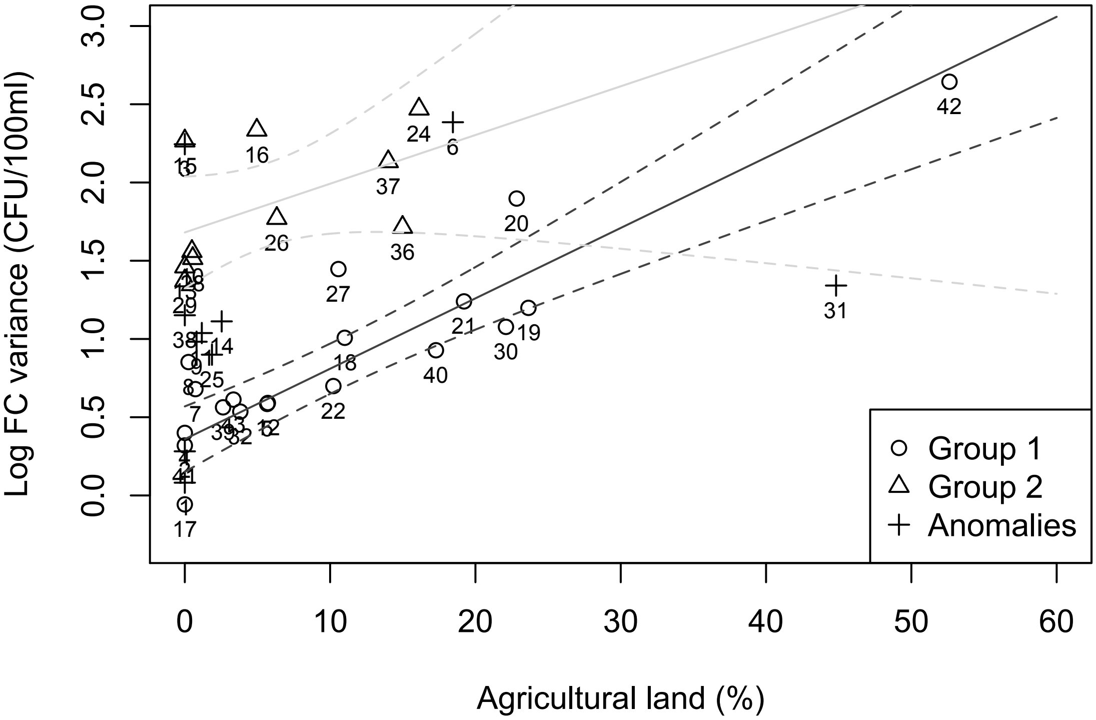

Figure 3.3.4 Fecal coliform (FC) variance ($\log_{10}$ of the standard deviation) plotted against the percentage of agricultural land within the upstream watershed. The significant relationship observed for Group 1 data is shown by the darker regression line and dashed 95% CI.

3.3.3 Exceedance of the BC raw water quality guideline

The frequency with which the BC raw water quality guideline was exceeded at each site increased in relation to the proportion of agricultural land within the upstream watershed (Fig. 3.3.5). Sample FC concentration did not exceed the guideline of 100 CFU 100ml^{-1} at 15 of the sites. The guideline was exceeded by fewer than 25% of the samples, at 20 sites. It was exceeded by between 25 and 50% of the samples at 6 sites and by more than 85% of the samples collected at 2 sites. The proportion of upstream agricultural land was significantly greater for sites where exceedance of the BC raw water quality guideline occurred in more than 50% of the samples compared to those where it occurred in less than 50% of the samples (ANOVA: F=6.32, p=0.001).

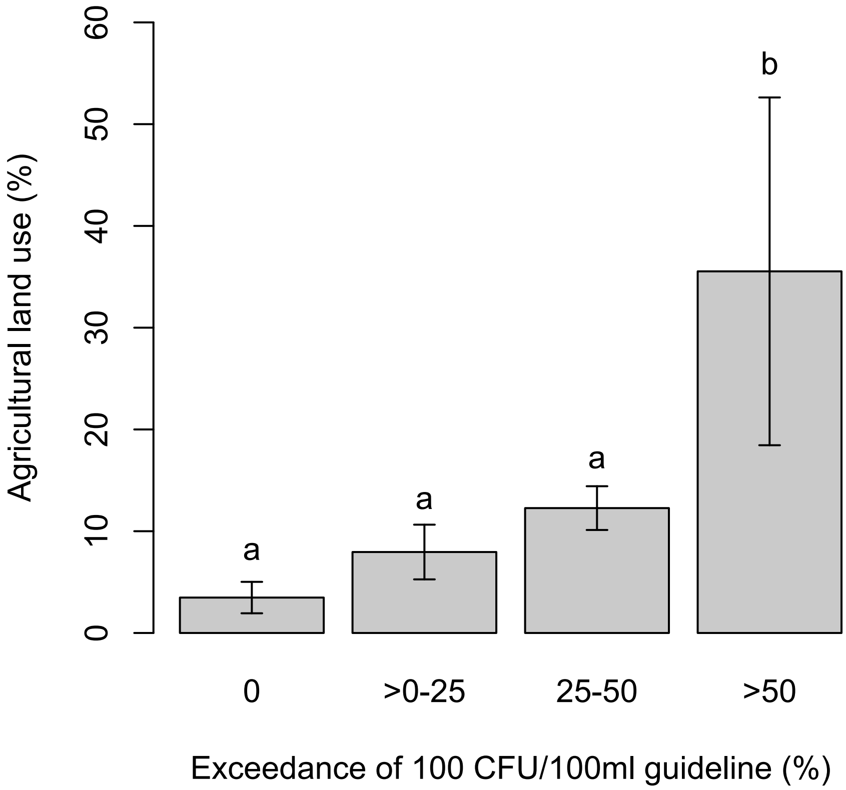

Figure 3.3.5 Percentage agriculture land of sites categorized according to frequency with which the BC raw water quality guideline (100 CFU $100ml^{-1}$) was exceeded at each site. Error bars show the standard error of the mean and different letters indicate a significant difference between means (determined by One-way ANOVA and Tukey pairwise comparison).

3.4 Discussion

A strong association was observed between land-use composition and surface water fecal contamination levels. The proportion of agricultural land-use within a watershed was the strongest explanatory factor of FC concentration variability among sites. Highly contaminated watersheds were further characterized by the additional influence of urban land. These associations demonstrate the capacity of fecal waste generated by livestock and human population activities within a watershed to increase fecal contamination levels in surface water. Fecal coliform concentration and variance and the frequency with which samples exceeded the BC raw water quality guideline increased in relation to the amount of agricultural land within the watershed. Greater values of these FC parameters in surface source water increase stress exerted on water treatment processes. Given this, agricultural development in a watershed upstream of surface source water is associated with a greater risk of human exposure to waterborne pathogens in drinking water.

3.4.1 Land-use type and fecal coliform concentration

Agriculture, urban, and young forest land-uses were found have a positive association with fecal contamination. Previous studies have also found greater surface water FC concentrations in watersheds where these land-use types are present compared to those where they are absent (Kistermann *et al.,* 2002; Dorner *et al.*, 2007). Animals associated with these land-use types, such as livestock, humans, and wildlife, especially avian species, generate diffuse fecal waste within the watershed (Tyrrel and Quinton, 2003; Meays *et al.,* 2006b). Strong evidence for the transport of these diffuse fecal contaminants into surface water is provided by the relationship between FC concentrations in source water and the presence of these land-use types. Transport is likely enhanced in watersheds containing agricultural and urban activity due to hydraulic modifications, such as the removal of vegetation and reduction of surface permeability (Atwill *et al.,* 2002; Tate *et al.,* 2004).

Land-use types associated with low densities of FC host organisms and lower FC transport potential were negatively associated with surface water FC concentration. Strongest negative associations with FC concentration were observed with sub-alpine, alpine, and glacial land. These land-use types are associated with low or absent livestock and human sources of fecal waste and are likely to be mainly influenced by low-density populations of wildlife. Furthermore, low winter temperatures at these altitudes result in snowpack and glacial ice that limit the transport of fecal contaminants by means of surface runoff (Ferguson *et al.,* 2003a).

The proportion of agriculture within a watershed was the most significant land-use factor determining FC concentration in downstream surface water; however, those with the highest FC concentration were further differentiated by the presence of more than 1.6% urban land. Very high FC concentrations appeared to result from the synergistic action of agricultural and urban land-use impacts on the production and transport of fecal contamination, which resulted in the greatest surface water fecal contamination (Field and Sullivan, 2003; Tyrrel and Quinton, 2003). Twelve of the 43 watersheds in this study had more than 12.5% agricultural land and a further eight of these sites had more than 1.6% urban land. These eight watersheds (18.6% of the total) are characterised by high surface water fecal contamination and indicate a high likelihood of there being comparatively high contamination within watersheds with similar land-use compositions.

Dorner *et al.* (2007) observed similar land-use and FC concentration interactions in five sub-watersheds within the Grand River Watershed, Ontario. Comparisons between sub-watersheds demonstrated a positive association between livestock density and urban development and FC concentration and variability. Greatest *Escherichia coli* concentrations were observed within an intensively farmed region, which had slightly higher FC concentration than an urban region. Surprisingly, Dorner *et al.* (2007) observed no significant difference between FC concentrations upstream and downstream of a wastewater treatment plant in Canagagigue Creek. In contrast, this study observed a dramatic increase in the range of FC concentrations associated with the presence of a sewage treatment plant on the Cheakamus River (site 4, located upstream the sewage treatment plant, had a FC concentration range of 1-15 CFU $100ml^{-1}$, while site 3, located downstream of the sewage treatment plant, had a FC concentration range of 1-2200 CFU $100ml^{-1}$, see Appendix A).

3.4.2 Land-use impact and fecal coliform concentration

Fecal coliform concentration was positively related to the proportion of agricultural land within the watershed, with the exception of those sites classified as anomalies. The strength of this relationship was surprisingly high given the many other land-use types and watershed characteristics that are known to influence FC variability. Agricultural cover appears to be an effective indicator of the presence and concentration of fecal contaminants within a watershed. Layuatey *et al.* (2007) found the proportion of cropland within the South Nation River watershed in Ontario to be the best determinant of the presence or absence of the bacterial pathogen *Listeria monocytogenes*. Cropland was found to be a better predictor than eleven other independent factors related to land-use, including the distance to nearest potential sources of contamination. A similar parameter, the percentage of improved pasture (for livestock) within catchments across the UK, explained 42% of the variability in mean FC concentration during high stream flow conditions (Kay *et al.,* 2008). A number of watersheds showed a limited relationship, as was the case for this study. Unexplained variance was mainly ascribed to point sources of contamination, such as sewerage infrastructure, and differences in weather conditions between studies. Similar factors are likely to account for the variability in the relationship between FC concentration and agricultural land observed in this study.

Three responses of FC concentration to the proportion of impacted land-use were identified amongst the sites examined. Fecal coliform concentration increased exponentially in relation to increasing agricultural land-use in Group 1 and 2 sites, but did not appear to be influenced by land-use in a third group of “anomalous” sites. In Group 1 fecal contamination appears to be caused mainly by agricultural inputs as the intercept passes very near the origin (intercept = 1.23). Baseline FC concentration was over an order of magnitude greater than Group 1 in the absence of agricultural land (intercept = 13.49).

The higher baseline FC concentration observed in Group 2 than Group 1 may have arisen due to other land-use and hydro-meteorological factors. The proportion of young forest in Group 2 watersheds was significantly greater than in Group 1 watersheds (Welch two-sample t-test: $t = -2.73$, $df = 27.79$, $p = 0.01$). This may have elevated baseline FC concentration in Group 2 as young forest was positively associated with fecal contamination (Fig. 3.3.1), likely due to fecal contamination from wildlife and recreational activities. Lower river discharge combined with higher temperatures may also have elevated FC concentrations in Group 2. Although the influence of temperature on FC survival times outside of an endothermic host organism is variable, FC concentration was positively related to temperature (maximum water temperature 20.4^0C) in Californian streams. This was ostensibly due to enhanced survival and re-growth of FC resulting from increased algal growth and decomposition of organic matter (Avery *et al.,* 2003; Teifenthaler *et al.,* 2009). The mean temperature of Group 2 was significantly greater than Group 1 (Welch two-sample t-test: t = -2.38, df = 29.46, p = 0.024). Significantly lower river discharge in Group 2 sites (Welch two-sample t-test: t = 2.26, df = 25.86, p = 0.033) may have enhanced these river conditions in summer, in addition to providing limited dilution of fecal inputs into the river.

Higher baseline FC concentrations for Group 2 than Group 1 could also be the result of point source contamination that was not accounted for by land-use data. The presence and age of storm water and sanitation infrastructure and the density of onsite septic systems and pit latrines within the watershed are common anthropogenic determinants of baseline fecal contamination levels (Walters *et al.,* 2010). Direct discharge of untreated sewage, farm waste, and septic tank leachate, into surface water dramatically increases FC concentration (Tyrrel and Quinton, 2003). Greater contributions from these sources would account for higher FC concentrations for Group 2 than Group 1 and may have resulted in the variability observed between sites for which FC concentrations were not related to agricultural land-use impacts. Quantifying these factors may provide valuable evidence with which to account for unexplained FC variability among sites.

Land-use data utilized in this study does not account for watershed characteristics such as slope, geology, and riparian vegetation, or the type and degree of management applied to potential sources of fecal contamination. Greater topographic complexity, intact and structured soil with macro-pores, and the removal of vegetation increase rainfall and snow-melt induced surface runoff and the transport of diffuse fecal contaminants into surface water (Ferguson *et al.,* 2003a). Conversely, strategies, such as preventing livestock from entering rivers or protecting riparian vegetation, can reduce contamination dramatically from one watershed to the next even though they may have a similar proportion of agricultural land-use (Tate *et al.,* 2004; Walters *et al.,* 2010). Detailed ground surveys would be required to substantiate the influence of these factors in this study.

The mean FC concentration was high for Site 6, Coldstream Creek at Kirkland (289±42 CFU $100ml^{-1}$), and low for Site 31, Peace River (4±4 CFU $100ml^{-1}$), in relation to the proportion of agricultural land in their respective watersheds (Fig. 3.3.3). These anomalies may have arisen due to differences in dilution resulting from very disparate river discharge volumes. The Coldstream Creek has an extremely low flow volume ($0.25\pm0.05m^3$ sec^{-1}), whereas the Peace River has an extremely high flow volume ($1463\pm36.1m^3$ sec^{-1}). Therefore, much less dilution of fecal inputs would have occurred in the Coldstream Creek than the Peace River. As a result, FC concentration was greater in the Coldstream Creek, despite the surrounding watershed having less agricultural land (18.45%) in comparison to the Peace River (44.82% agricultural land).

Group 1 sites, in which FC concentration increased in relation to increasing proportion of impacted land in the upstream watershed, demonstrated a positive association between FC variance and impacted land. This supports the assertion that fecal contamination in Group 1 resulted primarily from diffuse fecal contaminants within the watershed, whereas FC concentrations at other sites were determined to a greater degree by point-source contamination. The influence of directly discharged point-source fecal contamination on surface water FC concentration does not vary in relation to land-use and hydro-meteorological interactions to the same extent as it does for diffuse sources (Kay *et al.,* 2008).

Fecal contamination variability in source water can increase the risk of water treatment failure. High variability during hydrological events has led to chlorination disinfection processes being overwhelmed, e.g. in 2000 in Walkerton, Ontario (O'Connor, 2002b). Therefore, watersheds with greater land-use impacts are likely to be more vulnerable to fecal contamination variability associated with such events. This relationship stresses the need to consider land-use impact in the planning of adaptive measures to mitigate the anticipated stress on water treatment associated with precipitation variability (Delpa *et al.,* 2009).

3.4.3 Exceedance of BC raw water quality guideline

The current water quality guideline in BC for microbiological indicators sets the upper limit of acceptable FC concentration in raw source water receiving partial treatment (consisting of filtration or sedimentation and disinfection) at 100 CFU $100ml^{-1}$ (Warrington, 2001a). The proportion of FC samples at each site that exceeded this value increased in relation to increasing proportion of agricultural land within the upstream watershed. Variability in the frequency of guideline violation in relation to agricultural land was greater in watersheds with little agricultural land due to the influence of sites where FC concentration was not related to land-use. Watersheds with greater agricultural impact consistently violated the guideline. Due to this difference in variability, the proportion of upstream agricultural land was only significantly different from other categories where violation of the BC raw water quality guideline occurred with a frequency of over 50%. Greater frequency of water quality guideline violation in response to increasing agricultural impact further demonstrates the risk of water quality degradation associated with increased agricultural development.

3.5 Conclusions

Anthropogenic land-use was positively related to surface water FC concentration. The highest FC concentrations occurred in watersheds characterized by more than 12.5% agricultural and more than 1.6% urban land, accounting for 19% of the watersheds examined. Additional factors, such as sewage treatment, low dilution due to low river discharge, and higher temperatures were associated with a higher baseline FC concentration. Fecal coliform variance and the frequency with which samples violated the BC raw water quality guideline increased in relation to agricultural impacts. Greater FC concentration and variability in source water increases the stress exerted on water disinfection processes. Given this, agricultural development within a watershed is associated with a greater risk of human exposure to waterborne pathogens in drinking water. Variability in FC concentration was also observed among watersheds that did not show evidence of land-use impact on surface water fecal contamination. This was ostensibly due to point-source contamination. Further investigation of the presence of point-source contamination and watershed geological, riparian, and management characteristics should be undertaken to better explain such heterogeneity. This paper demonstrates the relationship between land-use and the risk of surface source water fecal contamination. This highlights the importance of source water protection, especially in watersheds with urban and agricultural land-use, for maintaining high quality source water and providing safe drinking water.

Chapter 4 The influence of hydro-climatic regime on seasonal variability of surface water fecal contamination

Abstract

Waterborne disease outbreaks are associated with source water fecal contamination that occurs due to the transport of fecal contaminants by means of rainfall and snowmelt-induced runoff. It is, therefore, important to understand the influence of runoff in driving seasonal fecal contamination variability, especially in light of changes occurring to runoff regimes as a result of climate change. This study examined surface water seasonal fecal coliform (FC) variability in relation to hydro-meteorological variability among watersheds in British Columbia (BC), Canada, with different runoff regimes. Significant associations between FC and hydro-meteorological variability were observed in 18 of the 43 sites examined. This corresponded to: 46% of the watersheds with snowmelt dominant (SD) surface runoff (n = 28), in which hydro-meteorological variability explained 64.8±4.8% of FC variability; 43% of sites with rainfall and snowmelt influenced (RSI) surface runoff (n = 7) in which hydro-meteorological variability explained 57.7±7.9% of FC variability; and 22% of sites with rainfall dominant (RD) surface runoff (n = 9) in which hydro-meteorological variability explained 45.7±12.7% of FC variability. The greater frequency of SD sites that demonstrated seasonal FC trends relating to hydro-meteorological variability than RD sites indicates that watersheds with SD runoff regimes are more prone to experiencing changes in seasonal FC trends as a result of climate change. Seasonal FC variability was only related to rainfall in RD watersheds in which rainfall events strongly induced

surface runoff and amplified river discharge. This was not the case where high FC concentration was observed during summer in RD watersheds, ostensibly due to fecal contaminant contributions from land-use activities in watersheds coupled with reduced dilution of these inputs.

Rising temperature has the capacity to alter seasonal patterns of fecal contamination. In SD watersheds with winter temperatures that remain below freezing, transport of fecal contamination will occur earlier in the year and may increase or decrease in spring in dependence on changes to snowpack accumulation in winter. Fecal coliform transport in summer is likely to decrease, especially in SD watersheds that currently show a strong association between FC concentration and rainfall. In watersheds that transition towards a RD runoff regime the risk of high surface water contamination will decrease in spring but increase during late fall or winter, concurrent with heavy rainfall events. Increased fall and winter rainfall is likely to only influence surface water FC concentration in watersheds that experience a strong response of runoff volume and river discharge to rainfall events. Variability among watersheds in this study indicate that the extent to which changes in runoff regime will influence surface water fecal contamination will vary among locations. This highlights the need for investigation of factors that enhance or mitigate the response of fecal contamination to hydro-meteorological factors to identify characteristics associated with greater vulnerability. Anticipating periods of peak surface source water fecal contamination can greatly contribute to the provision of safe drinking water.

4.1 Introduction

Waterborne disease is a major burden to human health throughout the world. Bartram and Cairncross (2010) estimated that approximately 2.4 million deaths and 7% of the global disease burden could be prevented through the provision of safe drinking water and improved sanitation. Even within developed countries, such as Canada, an element of risk persists in the production and consumption of drinking water. Canada has experienced a minimum of 80,000 cases of waterborne infections in the last 30 years and continues to experience severe disease outbreaks and endemic gastrointestinal illnesses due to fecal contamination of drinking water (e.g. Aramini *et al.,* 2000; O'Connor, 2002; Edge *et al.,* 2008).

Poor quality source water increases the physical and managerial stress on water treatment and supply systems (Perdek *et al.,* 2003; Lemmen *et al.*, 2008). Fecal contamination of source water has resulted in major waterborne disease outbreaks, such as those in: Milwaukee, Wisconsin, in 1993; Walkerton, Ontario, in 2000; and North Battleford, Saskatchewan, in 2001 (MacKenzie *et al.,* 1994; Stirling *et al.,* 2001; O'Connor, 2002a). Fecal contaminant variability in source water was associated with the incidence of gastroenteritis within the Metro Vancouver region of BC (Aramini *et al.,* 2000). The human and economic burden of these impacts indicates the need for source water protection, especially from fecal contamination, in order to protect public health (Davies and Mazumder, 2003; MacDougall *et al.,* 2007; Eggertson, 2008; Henson *et al.,* 2008).

Mobilization and transport of fecal contaminants into surface water occurs primarily through surface runoff and subsurface flow (Kistermann *et al.,* 2002; Dorner *et al.*, 2007; Kay *et al.,* 2008). Runoff is generated during hydro-meteorological events, such as rainfall and snowmelt, which increase soil saturation and overland flow (Ferguson *et al.,* 2003a; Boxall *et al.,* 2009). Land-use and management practices amplify or reduce the influence of hydro-meteorological events by altering watershed characteristics such as ground permeability and riparian vegetation (Tate *et al.,* 2004; Field and Sullivan, 2003). The interaction of these factors has been shown to determine fecal contamination levels in source water (Kay *et al.*, 2008).

Fecal coliform (FC) concentrations tend to be positively related to runoff, however, the influence of hydro-meteorological variability on seasonal surface water fecal contamination is challenging to quantify and observed relationships tend to be highly variable. In Ontario, FC concentration was lower during winter and early spring, ostensibly due to low temperatures minimizing contaminant transport (Dorner *et al.*, 2007). During the rainy season in the Gwangju Stream, Korea, FC concentrations were more variable than in the dry season, and were higher during wetter months than during dry months in Santa Catarina, Brazil (Cha *et al.*, 2010; Sigua *et al.*, 2010).

Efforts to determine quantitative changes in water quantity due to climate change have yet to be matched by efforts to anticipate changes in water quality. As a result, assessments of health impacts related to the influence of climate change on fecal contamination variability in surface water remain highly speculative (McMichael *et al.*, 2004; Confalonieri *et al.*, 2007; Lemmen *et al.*, 2008). Identifying the prevalence and strength of functional relationships between hydro-meteorological parameters and FC concentration can provide a basis for assessing the influence of climate change, such as early snowmelt, lower precipitation during summer, and increased precipitation during winter on surface water fecal contamination (Fraser, 2002; Bates *et al.*, 2008).

The province of BC in Canada has a steep climate gradient due to coastal and continental topographical influences on hydro-meteorological parameters. Runoff regimes vary among watersheds in relation to the timing and quantity of rainfall and snowmelt. For the purpose of this study, watersheds were divided into three different runoff regime categories: 1) rainfall-dominant (RD) watersheds, located in coastal BC, which are characterized by high river discharge during fall and winter due to rainfall; 2) snowmelt-dominant (SD) watersheds, located in the interior of BC, which are characterized by high river discharge during spring and summer in response to warming temperatures melting the winter snow accumulations; and 3) rainfall and snowmelt-influenced (RSI) watersheds, located at high elevation near the coast of BC, which are characterized by the influence of fall and winter rainfall as well as spring snowmelt.

4.1.1 Objectives

This study aimed to determine the extent to which seasonal FC variability was associated with rainfall and snowmelt among watersheds with different climate regimes in order to consider the influence of changes in runoff regime resulting from climate change on seasonal fecal contamination. It was hypothesized that seasonal FC variability will differ between watersheds with different runoff regimes in relation to the season of greatest surface runoff. The relative explanatory power of rainfall and snowmelt of FC variability within a watershed was expected to be relative to the proportion of surface runoff that is generated.

4.2 Data analysis and statistics

All available climate and FC data from the sites identified in chapter 2 were utilized in this study. Watershed runoff regimes were categorized as either rainfall-dominant or snowmelt-dominant in relation to the relative influence of rainfall and snowmelt on seasonal river discharge variability. Simple linear regression was employed to examine the extent to which river discharge variability was explained by three day cumulative rainfall at each site (expressed by the r^2 value). Sites were considered to be RD when river discharge was greatest in fall or winter, and due to rainfall. Sites were categorized as SD when river discharge was greatest in spring or early summer in response to snowmelt, although rainfall can also contribute to river discharge variability in these seasons. Sites where the river hydrograph was bimodal, due to snowmelt driven river discharge in spring and rainfall driven river discharge in fall, were categorized as RSI.

Mean seasonal FC, river discharge, and rainfall values were compared using a One-Way ANOVA. Multivariate linear regression (MLR) was used to model geometric mean (GM) FC variability in relation to rainfall and snowmelt variability. Modeling was carried out using mean monthly data in order to increase the accuracy of the annual trend for each parameter and obtain a standardised and appropriate sample number on which to perform regression analysis. Non-significant parameters (rainfall and/or river discharge) in the model were removed by stepwise deletion. Parameter coefficients in the model were considered to be statistically significant at an α level of 0.1 due to the high level of noise and variability inherent in FC data (after Lipp *et al.,* 2001b). The relative influence of rainfall and snowmelt on FC variability at each site was determined by their contribution to the explanatory power of the MLR model (Chevan and Sutherland, 1991).

It is important to be aware that both snowmelt and rainfall can potentially influence spring and summer FC variability in SD sites, and may act synergistically. The assumption was made that an association between FC and river-discharge variability in spring and summer was indicative of snowmelt driven fecal contamination. It was assumed that both rainfall and snowmelt were driving the association when rainfall and river discharge were both significantly associated with FC variability. It was assumed that when rainfall was driving the association FC variability was only related to rainfall.

The GM (calculated as GM = 10^{χ}, where χ = mean of $\log_{10}$-transformed values) was used to measure central tendency of FC concentrations, which follow a log10 normal probability density function in surface water (Wilkes *et al.,* 2009). All data handling, graphics, and statistical analysis were performed with the statistical software R (R Development Core Team, 2009).

4.3 Results

4.3.1 Temperature thresholds for runoff regimes

Temperature ranges differed among watersheds grouped by hydrographic-type. Mean winter (December, January, and February) temperatures of RD watersheds were above zero (95% confidence interval (CI) of winter mean temperature: 5.4^0C to 3.4^0C). Mean winter temperatures in RSI watersheds were slightly below freezing (95% CI of winter mean temperature: -0.2^0C to -1.7^0C) and SD watersheds had mean winter temperatures well below freezing (95% CI of winter mean temperature: -1.2^0C to -3.7^0C). These values indicate the range of mean winter temperatures associated with RD, RSI, or SD runoff regimes (Fig. 4.3.1).

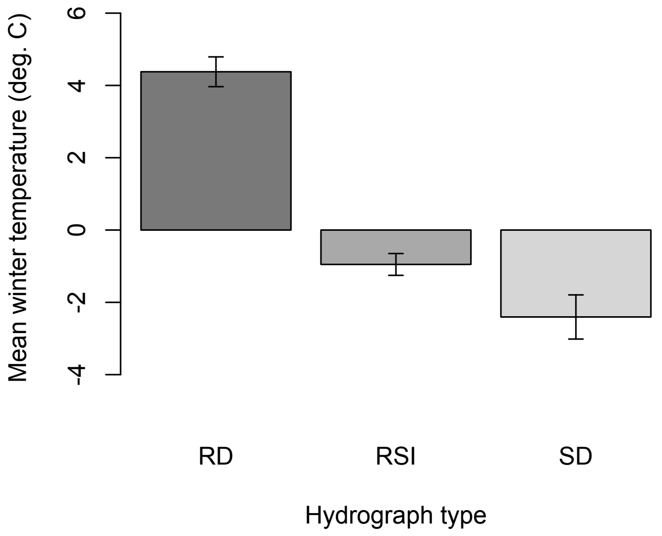

Figure 4.3.1 Mean winter (December, January, and February) temperatures of sites with rainfall-dominant (RD), rainfall and snowmelt influenced (RSI), and snowmelt-dominant (SD) river hydrographs. Error bars show standard error among sites.

4.3.2 Seasonal variability in parameters

A summary of FC, river discharge, and rainfall data along with watershed runoff regime and the season of peak value for each parameter are presented in Table 4.3.1. Mean seasonal FC concentrations differed significantly among the 30 sites. Differences were non-significant in sites with multiple or stochastic periods of high FC variability, as observed for most of the RSI sites (sites 1, 2, 4, 32, and 33). River discharge levels varied significantly between seasons at all sites, except site 31, where differences were marginally non-significant ($p = 0.065$). In contrast, rainfall levels were only significantly different between seasons at nine sites.

Table 4.3.1 Site name and number (#), number of samples available (n), watershed hydrographic-type (RD=rainfall-dominant, SD=snowmelt-dominant, RSI=rainfall and snowmelt influenced), and summary statistics of seasonal mean fecal coliform, river discharge, and rainfall values and season of peak value for each parameter (One-way ANOVA used to test for significant differences between seasons; $p<0.05$ indicates significance).

Site name	Site #	n	Hydrograph type	Fecal coliform			River discharge			Rainfall		
				Peak season	Mean, SE, and range of seasonal means (CFU/100ml)	One way ANOVA p	Peak season	Mean, SE, and range of seasonal means (m3/sec)	One way ANOVA p	Peak season	Mean, SE, and range of seasonal means (mm)	One way ANOVA p
Callaghan Creek	1	48	RSI	fall	1.26±0.13 (1-1.6)	0.599	summer	20.12±6.41 (7.87-37.49)	<0.001	winter	3.18±1.59 (0.64-7.71)	0.431
Callaghan Creek at Hway 99	2	64	RSI	spring	3.89±2.05 (1.22-9.93)	0.591	summer	20.33±5.25 (12.14-35.38)	<0.001	winter	2.84±1.08 (0.9-5.75)	0.117
Cheakamus River below sewage plant	3	39	RSI	winter	96.91±69.07 (2.64-298)	<0.001	summer	21.24±5.28 (12.14-36.25)	<0.001	winter	2.71±1.1 (0.86-5.75)	0.1
Cheakamus River on lake road	4	334	RSI	fall	1.51±0.31 (1-2.4)	0.613	summer	23.47±4.42 (15.5-34.85)	0.03	winter	3.55±1.68 (0-8.06)	0.092
Chilcotin River near Christie	5	126	SD	spring	5.25±1.66 (1.09-7.92)	0.011	summer	98.86±40.57 (39.3-218.5)	<0.001	fall	0.4±0.18 (0-0.82)	0.305
Coldstream creek at Kirkland	6	87	SD	summer	404.01±62.89 (305.25-588)	0.024	spring	0.2±0.11 (0.02-0.49)	0.003	spring	0.64±0.27 (0.09-1.23)	0.457
Columbia River at Birchbank	7	85	RSI	summer	4.04±0.93 (1.51-5.81)	0.016	summer	1870.67±214.84 (1493.67-2489.18)	<0.001	winter	1.34±0.22 (0.83-1.86)	0.489
Columbia River at Nicholson	8	164	SD	summer	3.81±1.75 (1-8.42)	0.004	summer	1.08±0.35 (0.56-2.09)	<0.001	summer	0.61±0.33 (0-1.5)	0.289
Columbia River at Waneta	9	124	SD	summer	15.38±4.48 (6.46-25.23)	<0.001	summer	2563.94±262.81 (2244.71-3344.77)	<0.001	winter	1.23±0.09 (1.04-1.46)	0.838
Cowichan River	10	147	RD	fall	30.58±12.94 (5.33-63.19)	<0.001	winter	52.01±21.37 (8.04-110.56)	<0.001	fall	2.87±0.56 (1.92-4.22)	0.517
Elk river at Hway 93	11	162	SD	summer	7.82±0.61 (6.59-8.95)	0.003	summer	21.36±8.04 (6.1-43.54)	<0.001	summer	0.63±0.25 (0.16-1.34)	0.341
Elk River at Sparwood	12	172	SD	summer	4.91±1.47 (1-8.04)	0.011	summer	41.18±11.06 (19.46-70.11)	<0.001	summer	1.17±0.49 (0.39-2.6)	0.07
Englishman River	13	163	RD	summer	34.13±8.71 (12.73-53.14)	0.001	winter	12.81±5.5 (2.45-27.07)	0.001	winter	4.4±1.37 (2.08-8.37)	0.195
Fraser River at Hansard	14	134	SD	summer	7.2±2.03 (2.4-12.25)	0.199	summer	480.57±175.82 (109.8-954.96)	<0.001	summer	1.5±0.51 (0.12-2.59)	0.404
Fraser River at Hope	15	42	SD	fall	48.23±9.48 (33.11-74.13)	0.849	summer	4.58±0.58 (3.41-6.19)	<0.001	fall	13.85±3.24 (6.1-21.84)	0.005
Fraser River at Marguerite	16	32	SD	fall	208.69±57.62 (127.9-379.53)	0.992	summer	1322.25±388.72 (485.53-2324.79)	<0.001	fall	2.32±0.73 (0.24-3.48)	0.112
Fraser River at Red pass	17	120	SD	fall	1.6±0.45 (1.13-2.95)	0.514	summer	41.56±23.48 (7.41-110.83)	<0.001	summer	2.09±1.07 (0.39-5.2)	<0.001
Kettle River at Carson	18	170	SD	summer	11.97±3.59 (2.03-18.9)	<0.001	spring	77.6±38.58 (13.49-174.44)	<0.001	spring	3.45±0.65 (1.52-4.41)	0.066
Kettle River at Midway	19	58	SD	summer	18.14±5.01 (3.68-26.12)	<0.001	spring	41.26±21.5 (7.43-97.43)	<0.001	spring	2.65±0.5 (1.91-4.06)	0.21
Koksilah River at Highway 1	20	171	RD	summer	79.71±44 (18.52-207.96)	<0.001	winter	9.37±4.35 (0.53-21.35)	<0.001	fall	2.82±0.58 (1.73-4.27)	0.433
Kootenay River at Creston	21	135	SD	summer	9.56±3.99 (2.89-21.15)	<0.001	summer	147.38±68.6 (38.96-346.68)	<0.001	fall	4.06±0.47 (2.95-5.04)	0.456
Kootenay River at Fenwick	22	592	SD	summer	7.3±1.45 (4-10.97)	<0.001	summer	150.41±57.65 (43.3-307.98)	<0.001	fall	2.25±0.39 (1.15-3)	0.524
Leech River	23	2557	RD	winter	1.55±0.3 (0.95-2.35)	<0.001	winter	21.01±12.29 (0.19-49.38)	0.005	winter	2.77±0.9 (0.56-4.8)	0.078
Mission creek at lakeshore rd. bridge	24	60	SD	winter	156.47±93.83 (23.47-433.63)	<0.001	spring	9.48±4.94 (0.92-20.19)	0.022	spring	0.78±0.27 (0-1.16)	0.553
Moyie River	25	186	SD	summer	7.87±1.54 (5.22-11.4)	0.166	spring	15.48±6.93 (4.39-35.1)	0.014	spring	3.43±0.83 (1.4-5.11)	0.883
Myers Creek	26	158	SD	summer	66.52±17.09 (30.77-111.97)	<0.001	spring	38.31±20.23 (5.55-89.5)	<0.001	winter	2.26±0.34 (1.52-3)	0.798
Nechako River	27	154	SD	spring	12.53±5.7 (3.7-28.44)	<0.001	summer	231.04±69.98 (128.81-437.75)	<0.001	summer	3.58±1.17 (0.73-6.22)	<0.001
Nicola River	28	199	SD	spring	22.45±9.56 (3.25-48.88)	0.027	spring	24.69±9.52 (8.31-51.45)	<0.001	summer	1.63±0.32 (0.8-2.22)	0.673
North Alouette	29	56	RD	summer	22.3±10.08 (5.5-48.05)	<0.001	winter	2.68±1.07 (0.9-5.65)	0.026	winter	19.17±6.24 (8.81-36.39)	0.039
Okanagan River at Oliver	30	199	SD	summer	12.58±3.37 (9.16-22.7)	<0.001	summer	14.26±2.32 (10.01-19.3)	<0.001	spring	1.85±0.25 (1.46-2.57)	0.578
Peace River	31	64	SD	summer	14.93±8.83 (5.16-41.38)	<0.001	winter	1465.8±57.74 (1316.66-1598.4)	0.065	summer	2.26±1.52 (0.06-6.74)	<0.001
Pend D'Orielle at Waneta	32	74	RSI	winter	1.89±0.67 (1-3.88)	0.292	summer	2443.94±295.37 (1898.75-3283.85)	<0.001	fall	3.85±0.26 (3.38-4.59)	0.98
Pend D’Orielle at US boarder	33	42	RSI	spring	1.13±0.03 (1.05-1.21)	0.523	summer	2399.42±176.26 (2187.37-2926.32)	<0.001	fall	2.51±0.65 (1.77-4.46)	0.34
Qunisam River near the mouth	34	60	RD	summer	20.58±7.33 (7.17-36.43)	<0.001	winter	9.15±2.48 (2.96-15.08)	0.037	winter	10.95±5.32 (2.5-25.49)	0.005
Salmon River at Falkland	35	222	SD	summer	80.42±23.59 (26.29-140.86)	<0.001	spring	3.32±1.72 (0.94-8.25)	<0.001	summer	1.05±0.13 (0.67-1.23)	0.405
Salmon river at Salmon Arm	36	55	SD	summer	92.1±14.86 (56.06-127.75)	<0.001	spring	4.42±1.87 (1.44-9.58)	<0.001	spring	1.1±0.28 (0.27-1.43)	<0.001
Salmon River at Silver Creek	37	44	SD	summer	136.66±21.51 (99-188.74)	0.01	spring	5.27±3.02 (1.32-14.2)	<0.001	fall	1.11±0.44 (0.4-2.34)	0.503
San Juan River	38	70	RD	fall	13.83±7.17 (4.71-35)	<0.001	winter	45.36±15.62 (5.69-77.13)	<0.001	fall	29.99±7.88 (10.11-48.11)	0.022
Similkameen River at Princeton	39	75	SD	summer	6.11±1.39 (2.43-9.08)	<0.001	spring	18.91±6.34 (6.98-33.76)	<0.001	fall	1.68±0.43 (0.9-2.88)	0.24
Similkameen River at US boarder	40	42	SD	spring	9.9±3.34 (1.94-17.76)	<0.001	spring	38.01±13.76 (15.52-77.11)	<0.001	winter	1.92±0.06 (1.83-2.1)	0.994
Sooke Lake	41	186	RD	summer	1.8±0.56 (1.02-3.45)	0.296	winter	1.94±1.16 (0.11-5.27)	<0.001	winter	3.23±1.15 (0.83-6.3)	<0.001
Sumas River at US border	42	44	RD	winter	575.12±113.26 (348.41-777.5)	0.296	winter	5.08±2.23 (1.05-11.47)	<0.001	winter	22.87±5.92 (8.9-37.64)	0.069
Thompson River	43	82	SD	fall	1.26±0.13 (1-1.6)	0.232	summer	20.12±6.41 (7.87-37.49)	<0.001	summer	3.18±1.59 (0.64-7.71)	0.053

4.3.3 Fecal coliform and hydro-meteorological relationships

Mean monthly FC variability was significantly related to hydro-meteorological (river discharge and rainfall) variability for 42 percent of the sites examined (18 out of 43); (Table 4.3.2). Grouped by hydrographic-type: RD watersheds had the lowest percentage of sites with significant FC concentration and hydro-meteorological associations (22%), RSI watersheds intermediate (43%), and SD watersheds the highest percentage (46%) of sites (Figure 4.3.2).

Table 4.3.2 Results for multivariate linear regression, where fecal coliform variability was modeled as a function of rainfall and river discharge variability (FC ~ Rainfall + River discharge), significant and near-significant parameters are given along with the full model r^2 and p-value.

Site name	Site no.	Hydro. type	Multivariate linear regression (FC~Rainfall+River discharge)					
			Rainfall		River discharge		Full model	
			t-value	p-value	t-value	p-value	Adjusted r2	p-value
Columbia River at Nicholson	8	SD	25.685	<0.001	2.042	0.071	0.987	<0.001
Elk river at Hway 93	11	SD	4.741	0.001	3.702	0.006	0.934	<0.001
Elk River at Sparwood	12	SD	8.245	<0.001	2.558	0.031	0.959	<0.001
Fraser River at Hansard	14	SD	2.980	0.015	-	-	0.441	0.015
Kettle River at Carson	18	SD	3.491	0.006	-	-	0.504	0.006
Kootenay River at Creston	21	SD	2.449	0.044	3.871	0.006	0.738	0.007
Kootenay River at Fenwick	22	SD	-	-	4.593	0.001	0.646	0.001
Nicola River	28	SD	-	-	2.603	0.026	0.344	0.026
Okanagan River at Oliver	30	SD	-	-	1.831	0.097	0.176	0.097
Peace River	31	SD	6.377	<0.001	3.388	0.010	0.817	0.001
Salmon river at Salmon Arm	36	SD	2.156	0.057	-	-	0.249	0.056
Salmon River at Silver Creek	37	SD	3.158	0.012	2.728	0.023	0.554	0.011
Similkameen River at US boarder	40	SD	-	-	4.236	0.002	0.603	0.006
San Juan River	38	RD	2.099	0.065	-	-	0.181	0.166
Sumas River at US border	42	RD	-	-	3.453	0.007	0.491	0.019
Cheakamus River below sewage plant	3	RSI	3.369	0.008	-	-	0.469	0.024
Cheakamus River on lake road	4	RSI	3.743	0.005	1.797	0.106	0.656	0.003
Columbia River at Birchbank	7	RSI	-	-	2.733	0.021	0.370	0.021

Among sites where associations were significant, hydro-meteorological variability explained the greatest amount of surface water FC variability in SD watersheds

(64.83±4.8%), less in RSI watersheds (57.7±7.9%), and the least in RD watersheds (45.7±12.7%). Thus, the proportion of sites in each hydrographic-type group that showed evidence of a relationship between hydro-meteorological and FC variability and the mean strength of those relationships increased with increasing proportion of snowmelt-induced surface runoff (Fig. 4.3.2).

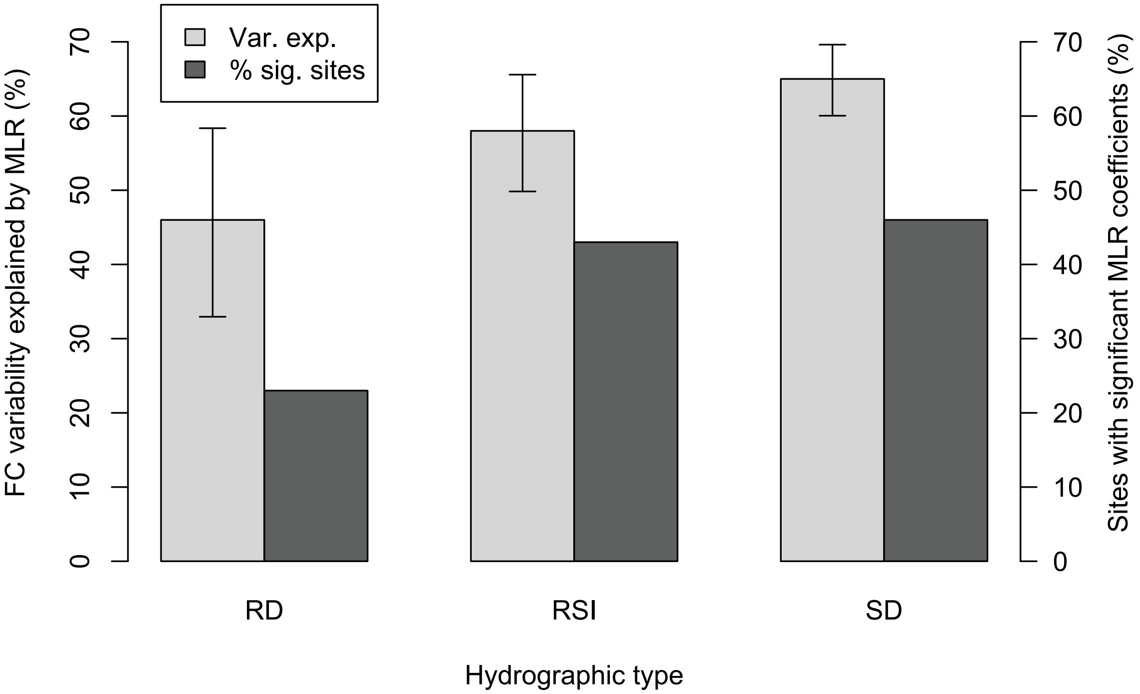

Figure 4.3.2 Percent fecal coliform (FC) variability explained by multivariate linear regression (MLR), where rainfall and river discharge were used as predictors of FC concentration, and the percentage of sites within each hydrographic group where MLR coefficients were significant (% sig. sites).

The prevalence of rainfall and river discharge associations with FC concentration varied between sites. Rainfall drove hydro-meteorological and FC associations at two RD sites (38 and 42). Fecal coliform variability was related to rainfall at three SD sites and snowmelt at four SD sites. Both rainfall and snowmelt were related to FC variability at six sites. Of these six sites, FC variability was more strongly related to rainfall than snowmelt at five sites. Fecal coliform variability was related to rainfall at two RSI sites and snowmelt at one RSI site.

The relative strength of rainfall and snowmelt relationships with seasonal FC variability within the three hydrographic-type groups was somewhat reflective of their influence on the hydrograph. Rainfall was the only parameter that explained FC variability within the RD group, in which there was no evidence for the influence of snowmelt. For sites within the RSI group, rainfall explained more FC variability than snowmelt (mean relative contribution of each parameter to the explanatory power of the MLR models: rain = 0.61, snow = 0.39, SE = 0.25). For sites within the SD group, snowmelt was marginally more influential than rainfall in explaining FC variability (mean relative contribution of each parameter to the explanatory power of the MLR models: rain = 0.48, snow = 0.52, SE = 0.08) (Fig. 4.3.3).

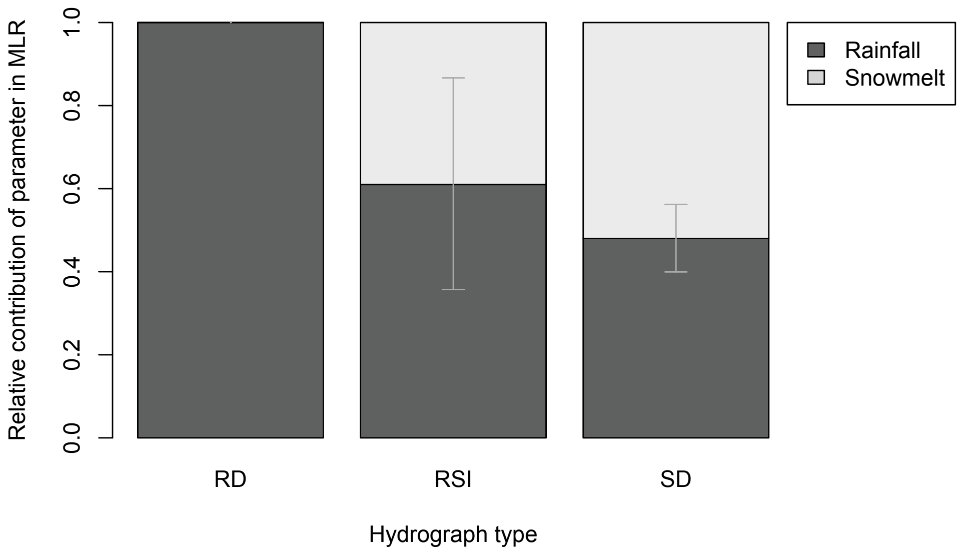

Figure 4.3.3 The mean relative explanatory power of rainfall and snowmelt towards mean monthly FC variability (determined by multivariate linear regression (MLR) models) within each hydrographic group (RD = rainfall dominant, RSI = rainfall and snowmelt influenced, SD = snowmelt dominant).

4.3.4 Hydro-meteorological characteristics of watersheds

Hydro-meteorological characteristics (temperature, rainfall, and river discharge) differed significantly between watersheds in which mean monthly FC variability was associated with either rainfall (R~FC), snowmelt (S~FC), or both rainfall and snowmelt (R&S~FC). Temperature variance was significantly lower in R~FC than R&S~FC, and intermediate for S~FC sites (6.8 ± 0.6^0C, 9.2 ± 0.5^0C, and 8.6 ± 0.2^0C, respectively; One-way ANOVA: $n=18$, $F=6.1$, $p=0.01$; $p<0.01$ for Tukey pairwise comparison of R~FC with R&S~FC). Mean rainfall was greater in R~FC sites than S~FC and R&S~FC sites (9.8±4.8mm, 1.7±0.1mm, and 1.6±0.5mm, respectively). The relationship between rainfall and river discharge was stronger in R~FC sites than S~FC and R&S~FC sites ($r^2=0.21\pm0.09$, 0.04 ± 0.02, and 0.02 ± 0.02, respectively) (Fig. 4.3.4).

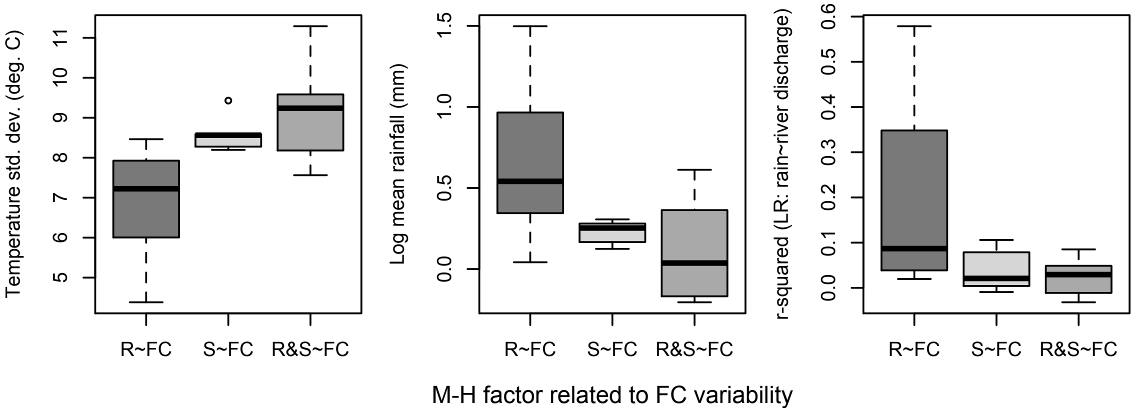

Figure 4.3.4 Hydro-meteorological (M-H) characteristics (standard deviation (std. dev.) of temperature (left), $\log_{10}$ mean rainfall (centre), and the association between rainfall and river discharge variability (indicated by the r^2 of linear regression (LR) between rainfall and river discharge) (right)) of sites grouped according to significant positive associations of rainfall, snowmelt, and rainfall and snowmelt with FC variability (abbreviated to R~FC, S~FC, and R&S~FC, respectively). The horizontal line shows the median, bottom and top of the boxes show the 25th and 75th percentiles, respectively. The whiskers show either the range or two standard deviations of the mean, whichever is smaller).

Rainfall and snowmelt were significantly related to FC variability among a number of SD sites. The relative strength of rainfall and/or snowmelt associations with FC variability was related to mean rainfall and temperature during the summer months (Fig. 4.3.5). Primarily R~FC sites (n=4) received a higher proportion and total volume of annual rainfall during the summer months (mean summer rainfall = 3.3±0.9 mm, 44% of annual precipitation) than primarily S~FC sites (n=6; mean summer rainfall = 2.2±0.6 mm, 29% of annual precipitation). The mean summer temperature was lower in R~FC sites than S~FC sites (15.2±1.0^{0}C and 18.5±0.7^{0}C, respectively. Wilcoxon Rank Sum test W=2, p=0.04).

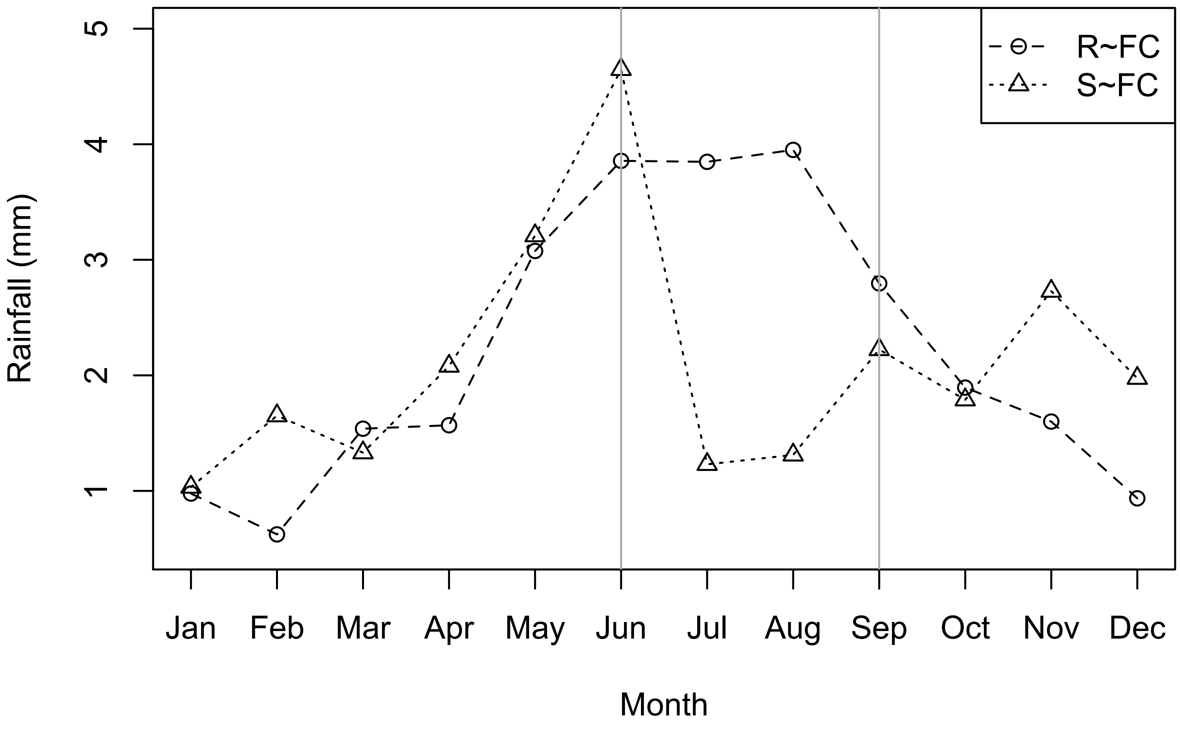

Figure 4.3.5 Mean monthly rainfall variability for two groups of SD sites defined by whether FC variability was primarily related to rainfall (R~FC, shown by dashed line) or snowmelt (S~FC, shown by dotted line). The summer period is indicated by the vertical lines.

4.3.5 Seasonal patterns of fecal coliform variability

In the two RD sites, highest mean seasonal FC concentration occurred in fall and winter. Only two of the 13 SD sites experienced high contamination in spring and the remaining 11 SD sites experienced highest FC concentration in summer. The 3 RSI sites experienced high contamination in summer, fall, and winter (Table 4.3.3). Peak FC concentration in fall and winter was related to rainfall, in spring to snowmelt, and in summer to rainfall at two sites, snowmelt at five sites, and both rainfall and snowmelt at six sites (Table 4.3.3).

Table 4.3.3 Frequency of sites with peak season of geometric mean (GM) fecal coliform (FC) concentration, categorized by hydrographic-type (rainfall-dominant (RD), rainfall and snowmelt influenced (RSI), and snowmelt-dominant (SD)) and significant positive association of FC concentration variability with rainfall, rainfall and snowmelt, or snowmelt (abbreviated to R~FC, R&S~FC, and S~FC, respectively).

Season of peak	Hydrograph type			Parameter sig. related to FC		
GM FC conc.	RD	RSI	SD	R~FC	R&S~FC	S~FC
Fall	1	1	0	2	0	0
Spring	0	0	2	0	0	2
Summer	0	1	11	3	6	3
Winter	1	1	0	2	0	0

Seasons of peak FC concentration among sites were significantly associated with watershed hydrographic type (Fisher's exact test (two sided) p = 0.01). Peak FC concentration in fall and winter was associated with RD and RSI sites, whereas peak FC concentration in spring and summer was associated with SD sites (Fig. 4.3.6). Seasonal FC variability was also significantly associated with hydro-meteorological parameters associated with FC variability (Fisher's exact test (two sided) p = 0.03). Peak FC concentration in fall and winter was associated with R~FC, in spring with S~FC, and in summer with R&S~FC. These associations are illustrated in Figure 4.3.6 where positive deviations from the expected ratio of categories are indicated by black bars and negative deviations by grey bars.

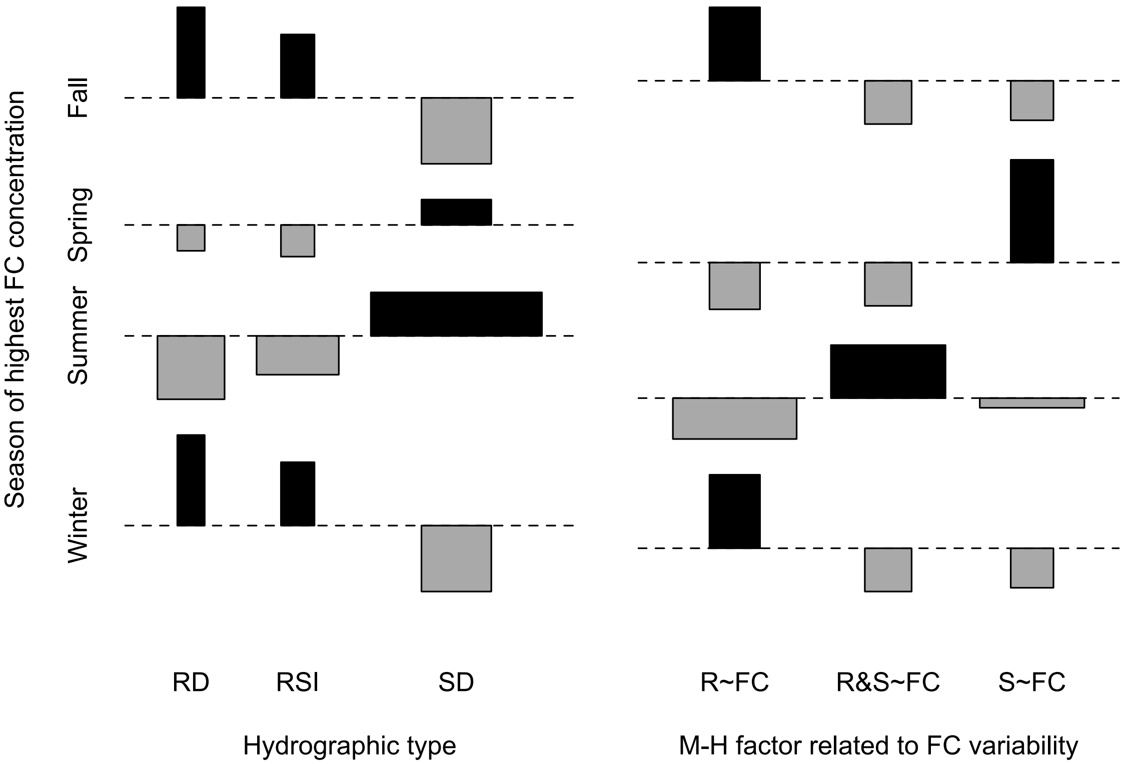

Figure 4.3.6 A Cohen-Friendly association plot indicating significant associations between seasonal fecal coliform (FC) variability and hydrographic type (RD = rainfall-dominant, RSI = rainfall and snowmelt influenced, and SD = snowmelt-dominant) and hydro-meteorological (M-H) factor related to fecal coliform (FC) variability (R~FC, R&S~FC, and S~FC = rainfall, rainfall-&snowmelt, and snowmelt associations with FC, respectively). Bar height or depth indicates the respective positive (black) or negative (grey) deviation from expected values. The baseline, therefore, indicates independence, and the area of the box is proportional to the difference in observed and expected frequencies.

Seasonal variability in river discharge, rainfall, and FC concentration was strongly associated with temperature variance. In general, winter and fall peak river discharge, rainfall, and FC concentration were associated with low temperature variance, while summer and spring peak values were associated with high temperature variance (Fig. 4.3.7). Sites with peak river discharge in winter (w) (n = 2) had significantly lower mean temperature variance (std. dev. = 4.7±0.4^{0}C) than those with peak river-discharge in summer (su) and spring (s) (n = 10 and 6; std. dev. = 8.5±0.4^{0}C, and 8.6±0.2^{0}C, respectively; One way ANOVA: F = 6.3, n = 18, p = 0.01; Tukey pairwise comparison: p = 0.01 for w-su and p = 0.01 for w-s). Temperature variance was lowest for sites with peak rainfall in winter (n = 5), followed by fall (f) (n = 3), spring (n = 4), and summer (n = 6) (7.1±0.6^{0}C, 7.4±1.6^{0}C, 8.5±0.08^{0}C, and 9.1±0.6^{0}C, respectively). Sites with peak FC concentration in fall (n = 2) and winter (n = 2) had a significantly lower mean temperature variance (5.8±1.4^{0}C and 6±0.9^{0}C, respectively) than sites with peak FC concentration in summer (n = 12; mean temperature variance = 8.8±0.3^{0}C; One way ANOVA: F = 6.8, n = 18, p = 0.004; Tukey pairwise comparison: p = 0.01 for f-su and p = 0.03 for w-su). Sites with peak FC concentration in spring (n = 2) had a very similar mean temperature variance to those with peak contamination in summer (8.4±0.2^{0}C).

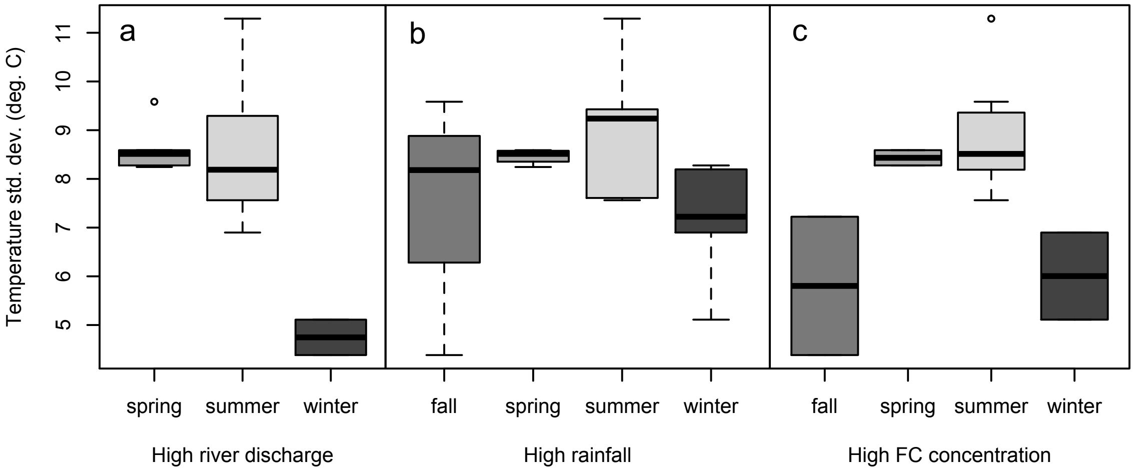

Figure 4.3.7 Temperature standard deviation (std. dev.) for sites grouped by season of highest river discharge (panel a), rainfall (panel b), and fecal coliform (FC) concentration (panel c), the horizontal line shows the median, bottom and top of the boxes show the 25th and 75th percentiles respectively, and the whiskers show either the range or two standard deviations of the mean, whichever is smaller.

4.3.6 Hydro-meteorological characteristics and seasonal patterns

Hydro-meteorological characteristics associated with different seasonal FC variability (Table 4.3.4) can be summarized as follows:

1) High FC contamination in fall and winter was significantly associated with rainfall within RD and RSI watersheds (Fig. 4.3.6). These watersheds were characterized by low temperature variance (Fig 4.3.4) (mean winter temperatures above freezing), high rainfall in fall and winter, and high river discharge in winter, driven by rainfall.
2) High FC contamination in spring was significantly associated with snowmelt within SD watersheds (Fig. 4.3.6). These sites were characterized by high temperature variance (Fig 4.3.4), high river discharge in early spring, high summer temperatures and low summer rainfall.
3) High FC contamination in summer was significantly associated with rainfall and snowmelt within SD watersheds (Fig. 4.3.6). These watersheds were characterized by high temperature variance (Fig 4.3.4) (winter mean temperatures below freezing), high summer rainfall (Fig. 4.3.5) and high river discharge in late spring.

Table 4.3.4 Characteristics of different seasonal fecal coliform (FC) variability: hydro-meteorological (M-H) drivers associated with FC (R~FC, R&S~FC, and S~FC = rainfall, rainfall-&snowmelt, and snowmelt associations with FC, respectively), hydrographic type (RD/RSI = rainfall-dominant and rainfall and snowmelt influenced hydrographs, and SD = snowmelt-dominant hydrograph), and season of high rainfall and river discharge.

High FC	M-H driver	Hydro type	Temp. var.	High rainfall	High river dis.
Fall/winter	R~FC	RD/RSI	Low	Fall/winter	Winter
Spring	S~FC	SD	Medium	Spring/winter	Spring (early)
Summer	R&S~FC	SD	High	Summer	Spring (late)

Monthly variability in FC concentration, rainfall, and river discharge associated with different seasonal patterns of fecal contamination are illustrated by three example sites: 1) the Nicola River at Spences bridge is an example of a SD and S~FC site (SD(s)); 2) the Kettle River at Carson a SD and R~FC site (SD(r)); and 3) the San Juan River near Port Renfrew a RD and R~FC site (RD(r)).

Mean winter and summer temperatures, annual rainfall, and elevation values for each example site are illustrated in Figure 4.3.8. Differences in mean values between sites were significant (ANOVA $p<0.05$ for each set of comparisons) and illustrate the general characteristics of sites associated with spring, summer, or fall/winter high FC contamination (as described in Table 4.3.4 above).

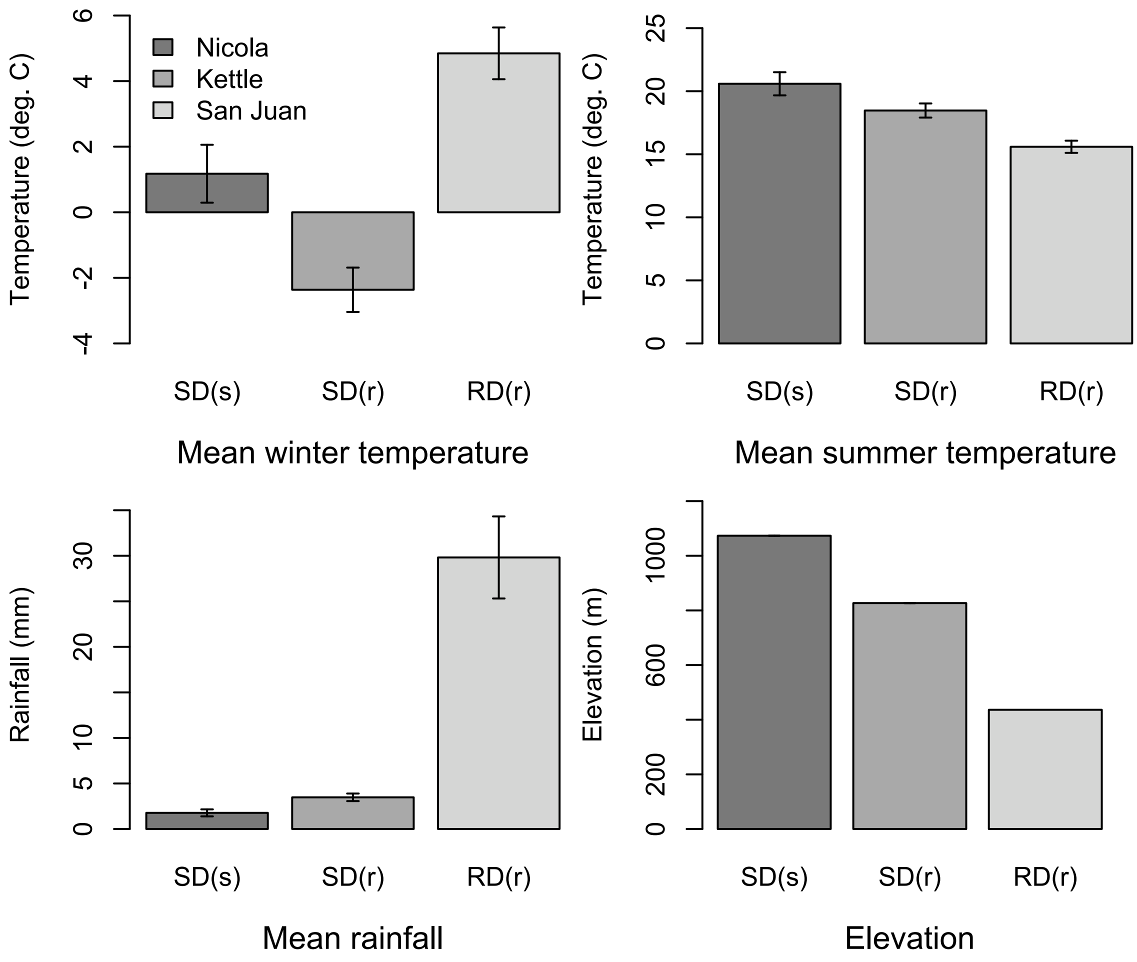

Figure 4.3.8 Mean and standard error for winter and summer temperatures, annual rainfall, and mean elevation for the Nicola River (SD(s) = Snowmelt-dominant and snowmelt driven FC variability), Kettle River (SD(r) = Snowmelt-dominant and rainfall driven FC variability), and San Juan River (RD(r) = Rainfall-dominant and rainfall driven FC variability).

Time series of mean monthly FC concentration, river discharge, and rainfall variability are shown in Figure 4.3.9 to illustrate the relationships between these variables. Data for each parameter were standardised to a scale of 0-1 (using the equation: (V - min V) / (max V - min V), where V represents the value of the variable in the original data set) so that variability can be clearly seen for each parameter. Least significant difference intervals are shown for mean monthly FC concentration to indicate the robustness of the trend. The variance of monthly FC concentration increased with the mean at each site. In the SD(s) site FC concentration increased during the freshet event in March and April. In the SD(r) site, FC concentration increased during the freshet but then followed rainfall variability, which remained high through the summer. In the RD(r) site FC concentration was highest in September and October, apparently driven by rainfall-induced surface runoff (Figure 4.3.9, panels a, b, and, c, respectively).

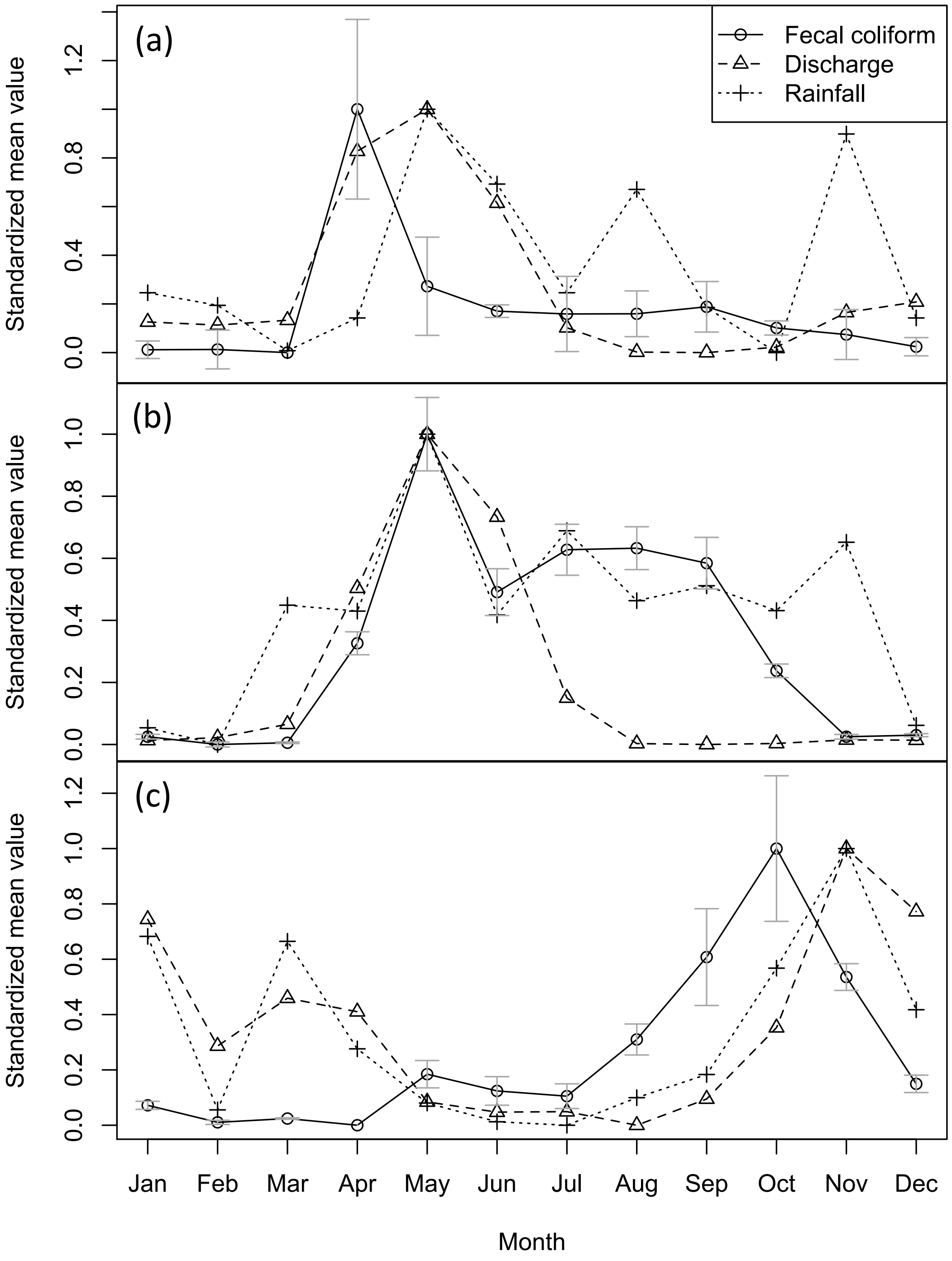

Figure 4.3.9 Time series of standardized mean monthly rainfall, river discharge, and fecal coliform (FC) concentration values for the Nicola River (a), Kettle River (b), and San Juan River (c). Least significant difference intervals for mean FC concentration indicated by the bar and whiskers.

The influence of rainfall and river discharge in driving FC variability among these three sites was quantified by the relative contribution of rainfall and river discharge as parameters in the MLR model for each site. River discharge contributed 89% to the total FC variance explained by the MLR model (51%) for the Nicola River. The positive t-value ($t = 3$) describes the relationship between river discharge and FC variability as positive and the p-value of less than the α value of 0.1 ($p = 0.014$) indicates that this relationship is significant. In contrast, rainfall was a non-significant ($p = 0.19$) parameter that was negatively related to FC variability ($t = -1.4$) and only contributed to 11% of the MLR explanatory power. The relative contribution of rainfall was greater (63%, $p = 0.04$) than river discharge (37%, $p = 0.2$) in the MLR model for the Kettle River (total explanatory power = 62%), and both of the parameters were positively related to FC variability ($t = 2.3$ and 1.3 for rainfall and river discharge, respectively). The MLR model for the San Juan River explained the least amount of FC variance (33%). Rainfall contributed 64% of the explanatory power, and had a significant positive relationship with FC variability ($t = 2.1$, $p = 0.06$). River discharge contributed 36%, and had a non-significant negative relationship with FC variability ($t = -1.8$, $p = 0.11$) (Fig. 4.3.10).

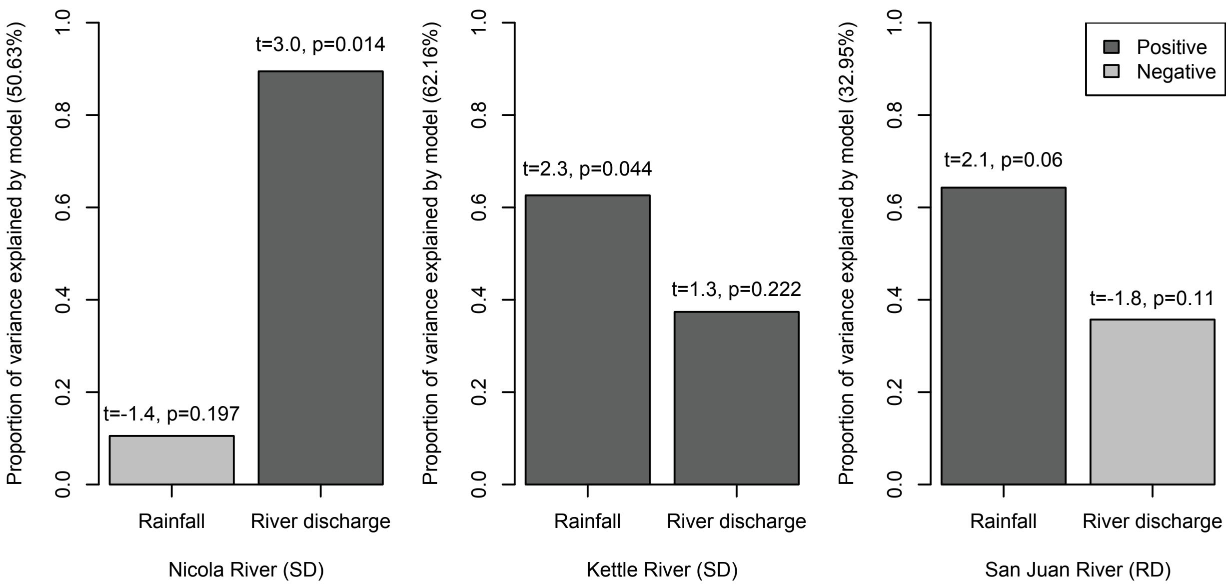

Figure 4.3.10 The relative contribution of rainfall and river discharge as explanatory variables of mean monthly fecal coliform variability, in multivariate linear regression models, for the Nicola, Kettle, and San Juan Rivers (illustrated in Figure 4.3.9), given by the r^2 contribution averaged over orderings among regressors. The test statistic (t) and p-values (p) for each coefficient are given above each bar.

4.4 Discussion

Seasonal patterns of fecal contamination in the surface water locations examined in this study were strongly related to hydro-meteorological (river discharge, in some cases used to indicate snowmelt, and rainfall) variability in some cases (>90% of mean monthly FC concentration explained at three sites) and failed to show evidence of any relationship in others (no significant relationship observed for 58% of the sites). Sites that demonstrated significant associations between seasonal hydro-meteorological and FC variability provide strong evidence that hydro-meteorological parameters are capable of influencing seasonal FC transport by means of surface runoff generation. This relationship implies that seasonal shifts in hydro-meteorological variability, which alter the runoff regime, will have a corresponding influence on surface water fecal contamination. The large proportion of sites examined that did not show significant evidence of hydro-meteorological influences on seasonal FC variability suggest that a significant proportion of sites in this study are likely to be unaffected by changes in runoff regime.

Variability in the strength and even direction of relationship between hydro-meteorological variability and FC concentration among surface water sites is common (Schaffter *et al.*, 2004; Wilkes *et al.*, 2009). This makes it challenging to anticipate the magnitude of response of surface water contamination levels to changes in climate. The 42% of sites in which hydro-meteorological factors were seen to influence FC variability is likely to be conservative, as FC data obtained by grab samples is seldom representative of true variability (Meays *et al.*, 2006a). This was evidenced by the number of highly inflated zero counts and large outlying values observed for many sites. The low frequency with which FC concentrations were measured limited the extent to which relationships between FC concentration and hydro-meteorological variability could be identified. In spite of such limitations, the absence of hydro-meteorological and FC associations suggests that FC variability at a number of sites is stochastic or driven by factors not significantly influenced by hydro-meteorological variability.

Snowmelt-induced runoff was more consistently related to FC variability than rainfall-induced runoff. This was evidenced in a number of ways. Firstly, stronger seasonal FC trends for SD than RSI and RD sites, illustrated by the significance of seasonal FC variability, suggests that a greater amount of FC variability in surface water is generated by seasonal hydro-meteorological variability. Secondly, the proportion of sites for which FC variability was significantly associated with hydro-meteorological variability was greatest in SD, and lowest in RD watersheds (46%, 43%, and 22% for SD, RSI, and RD sites, respectively). Thirdly, the proportion of mean monthly FC variability explained by hydro-meteorological variability was greatest in SD sites and lowest in RD sites (65%, 58%, and 46% for SD, RSI, and RD sites, respectively). It is worth noting, however, that the low sample number of RD sites (n = 9), and the low proportion of these that showed evidence of FC concentration being related to hydro-meteorological variability, resulted in only two RD sites from which to estimate the explanatory power of FC variability as a function of hydro-meteorological variability. Therefore, this estimate is much less reliable than that for SD sites, which was generated from a sample number of 13.

Fecal contamination in RD watersheds tended to be greater in summer despite low rainfall and river discharge levels. McDonald *et al.* (2008) observed similar trends in rivers located within a protected wilderness area in Scotland. Fecal coliform concentrations were significantly greater in summer despite this being the season of lowest rainfall. This was attributed to greater numbers of visitors coupled with low flows in summer. Low river discharge reduces dilution of fecal contaminants, especially from activities that release fecal contamination directly into water-bodies. These include increased discharge of fecal waste from farms, contributions from wildlife, and human recreation activities, such as bathing and camping (Meays *et al.,* 2006b; Teifenthaler *et al.,* 2009; Sigua *et al.*, 2010). Under such circumstances, the influence of summer rainfall would be disproportionately high due to elevated fecal contaminant levels within the watershed coupled with limited dilution. The opposite, i.e. keeping cattle indoors and reduced recreation activity, may account for the low FC concentrations observed in some

RD watersheds during fall and winter. High FC concentrations in summer may have also resulted from increased FC survival and in situ growth, which is stimulated by the combination of high temperatures, organic matter, and dissolved solids (Teifenthaler *et al.,* 2009).

Land-use activities during the summer may have contributed to the stronger relationships between hydro-meteorological and FC variability observed in SD watersheds. The addition of fecal contaminants within SD watersheds during summer would have accentuated the positive relationship between FC concentration and surface runoff, which tends to be high during this season. Conversely, this would obscure relationships between surface runoff and FC contamination in RD watersheds by increasing the influence of surface runoff on FC concentration in summer, when precipitation and river discharge are at their lowest.

Evidence for rainfall driven seasonal FC variability in RD sites only occurred in watersheds where river discharge variability was strongly related to rainfall (rainfall explained >50% of river discharge variability). This indicates that the relationship between rainfall-induced surface runoff and river discharge must be relatively high in order to influence seasonal FC variability in rivers. The high proportion of RD sites that failed to show FC and hydro-meteorological associations may have been due to the incapacity of rainfall-induced surface runoff to transport fecal contaminants into surface water. This could have resulted from modifications to the landscape that impeded rainfall-induced surface runoff, such as entrapment in retention ponds, and artificial dams that disrupt the relationship between surface runoff and river discharge variability (Fraser, 2002; Ferguson *et al.*, 2003a; Arnone and Walling, 2007).

Hydro-climatic regime among sites determined the relative influence of rainfall and snowmelt in driving different seasonal fecal contamination trends. Runoff regimes were determined by winter temperatures, which when high increased rainfall and when low increased winter snowpack accumulation. As temperature variance increased, the fraction of precipitation as rain at each site decreased along with the proportion of rainfall-induced surface runoff. The varying degree of rainfall or snowmelt driven surface runoff was reflected in the relative strength of rainfall and river discharge associations with FC variability. In RD watersheds, where snowmelt is absent or negligible, rainfall was solely responsible for surface runoff driven FC variability. In the RSI group, rainfall accounted for an average of 61% of the explained FC variability, which roughly reflects the ratio of 2:1 sites where rainfall was the more significant hydro-meteorological parameter. Surprisingly, 48% of explained FC variability in SD watersheds was attributed to rainfall. There may be an element of overestimation due to some sites having similar rainfall and snowmelt variability. In two SD watersheds (sites 8 and 31), however, rainfall explained around 90% of FC variability, and was, therefore, clearly driving the association. Much of the variability in strength of relationship between rainfall and FC variability among SD watersheds was explained by lower summer temperatures and higher summer rainfall in R~SD sites compared to S~FC sites.

Climatic characteristics associated with different seasonal trends in FC variability indicate the influence that changes in runoff regime, occurring due to climate change, will have on seasonal FC variability. In southern BC, winter temperatures have increased by 1.8^{0}C and summer temperatures by 1.2^{0}C between 1895 and 1995. Resultant changes in the fraction of rainfall and snowfall during fall and winter and reduced summer precipitation are changing runoff regimes and river hydrographs (Schnorbus *et al.*, 2011; WDFW, 2011). For example, the upper Similkameen River is experiencing earlier peak discharge in spring, lower summer flows, and greater variability in fall (Fraser, 2002). These changes to runoff regime will cause a corresponding shift in fecal contaminant transport potential by means of rainfall and snowmelt-induced surface runoff and subsurface flow (Dorner *et al.*, 2007).

The runoff regime and river hydrograph within a watershed will change most rapidly around the threshold temperature values calculated for SD, RSI, and RD runoff regimes. Mean winter temperatures below -1.2^{0}C characterized snowmelt-dominant watersheds. Many watersheds in the interior of BC will continue to experience mean winter temperatures below this threshold. Warming trends in these watersheds are projected to increase snow pack accumulation and snowmelt-induced surface runoff in spring (Schnorbus *et al.*, 2011). Higher temperatures will induce snowmelt around four weeks earlier in the year by 2080 and reduce summer rainfall by 10-20% (WDFW, 2011). As a result, fecal contaminant transport in surface water is likely to occur earlier in the year, and be greater in spring but lower in summer. These changes are analogous to a shift from the hydro-meteorological and FC trends illustrated by the Kettle River (site 18, Fig. 4.3.9b) to those illustrated by the Nicola River (site 28, Fig. 4.3.9a).

If the mean winter temperature within a watershed were to increase towards a positive value (threshold observed among sites -0.21^{0}C), it would transition from a snowmelt-influenced to a rainfall-dominant runoff regime. This transition is expected to cause an increase in surface runoff and flood magnitude (WDFW, 2011). The proportion and total amount of rainfall in fall and winter would increase, causing a corresponding decrease in snowpack accumulation and spring snowmelt (Schnorbus *et al.*, 2011). This would likely cause a corresponding decrease in the risk of high surface water contamination in spring but potentially increase fecal contamination during late fall and winter. This impact would alter hydro-meteorological and FC trends from those observed for site 28 (Figure 4.3.9a) towards those observed for site 38 (Figure 4.3.9c). Although these examples provide an illustration of how future climate change may influence seasonal fecal contamination, the response is likely to vary among watersheds. Runoff regimes are not discrete but exist on a continuum, along which the influence of runoff on fecal contaminant transport is likely to vary. This can be seen in the variability observed in the relationship between FC concentration and hydro-meteorological variability among the sites within the different hydrographic groups. Furthermore, climate change will also influence land-use activities and water management within watersheds, which has the capacity to influence surface water fecal contamination along with changes in the runoff regime.

4.5 Conclusions

Seasonal FC variability in surface water was strongly influenced by climate in some watersheds but apparently unrelated to climate in others. Watersheds with SD runoff regimes are more likely to have seasonal FC trends that relate to hydro-meteorological variability than those with RD runoff regimes, and thus are more prone to experiencing a shift in these trends as a result of climate change influences on the runoff regime. High FC concentrations were often observed during summer in RD watersheds, ostensibly due to fecal contaminant contributions from land-use activities in watersheds coupled with reduced dilution. There is little evidence to suggest that current seasonal FC variability observed in RD watersheds will be strongly influenced by climate change.

In SD watersheds with mean winter temperatures that remain well below freezing, transport of fecal contamination will occur earlier in the year and may increase or decrease in spring depending on changes occurring to snowpack accumulation in winter. Fecal coliform transport in summer is likely to decrease, especially in SD watersheds that currently show a strong association between FC and rainfall. In watersheds that transition towards a RD runoff regime the risk of high surface water contamination will decrease in spring but increase during late fall or winter, concurrent with heavy rainfall events. Increased fall and winter rainfall will only influence surface water FC concentration in watersheds that experience a strong response of runoff volume and river discharge to rainfall events.

The extent to which these changes in runoff regime will influence surface water fecal contamination will vary among watersheds. Further investigation is required to identify factors that enhance or mitigate this association and provide further evidence with which to assess the capacity for changes to the runoff regime within a watershed to alter surface water fecal contamination variability.

Chapter 5 The influence of inter-annual hydro-meteorological variability on surface water fecal contamination

Abstract

Intense rainfall and snowmelt events increase surface water fecal contamination by means of surface runoff transportation of fecal contaminants. Greater fecal contaminant transport is likely to occur due to the projected increase in the frequency of these events at mid latitudes under projected climate change. This has the potential to increase surface source water fecal contamination, an important consideration in the mitigation of waterborne disease risk. The capacity for seasonal and annual changes in hydro-meteorological parameters (surface runoff, river discharge, rainfall, and temperature) to influence surface water fecal contamination was examined by measuring their association with fecal coliform (FC) concentration. Seven years of continuous FC data (2000-2006), with a minimum bi-weekly sampling frequency, were collected for 19 surface water sites across southern British Columbia (BC). Inter-annual relationships between FC concentration and hydro-meteorological variability were examined using three distinct measures of variability: 1) Long-term trends, obtained by time-series decomposition; 2) annual and seasonal deviations from the inter-annual mean; and 3) deviations due to the 2002/03 El Niño event relative to non-El Niño, termed neutral, years. Total annual and seasonal FC concentration appeared to be influenced by rainfall and river discharge for 58% (11 out of 19) of the sites. Minimum mean annual FC concentration occurred with greatest frequency among sites during the EL Niño year of 2002/03, during which precipitation across southern BC was 10-60% below the climate

norm. Long-term FC variability was more frequently associated with river discharge (8 out of 19 sites, mean Spearman's correlation: $\rho = 0.51 \pm 0.06$) than rainfall (3 out of 19 sites, mean Spearman's correlation: $\rho = 0.45 \pm 0.1$). These associations were observed in winter, the season of greatest precipitation, and for spring, the season of greatest snowmelt, but not in summer or fall. Warmer temperatures in winter were associated with greater rainfall in the Cowichan River, a RD watershed at the southern tip of Vancouver Island. This appeared to drive a corresponding increase in mean FC concentration in the river. Given that winter temperatures are projected to rise and runoff regimes to shift towards greater rainfall dominance, these changes are likely to occur in many watersheds in BC over the coming century. The El Niño event in 2002/03 provided further evidence of inter-annual precipitation variability influencing FC concentration. A mean reduction in river discharge during the spring and summer, among all the sites in the study, was associated with a mean reduction in FC concentration. Rainfall, however, appeared to have little influence on FC concentration. These interactions demonstrate the capacity of changes to seasonal and annual meteor-hydrological conditions to cause corresponding changes to surface water fecal contamination. These changes are important to consider for the future management of surface source water and the production of safe drinking water.

5.1 Introduction

Rising temperatures are anticipated to increase mean annual precipitation in British Columbia (BC), Canada (Bates *et al.,* 2008). This will cause a corresponding increase in the volume and timing of rainfall and snowmelt-induced surface runoff (Schnorbus *et al.* 2011). An increase in surface runoff volume has the capacity to mobilize a greater proportion of fecal contamination from within a watershed into surface source water (King and Monis, 2007; Boxall *et al.,* 2009). This has been demonstrated in transport models and field studies, where peak pathogen loads were shown to occur at times of high surface runoff (Dorner *et al.,* 2006 and 2007). Projected increases in precipitation will increase soil saturation and intensify runoff and fecal contaminant transport within BC's watersheds. This has the capacity to increase the risk of source water exposure to waterborne pathogens (McMichael *et al.*, 2004; Confalonieri *et al.*, 2007; Lemmen *et al.*, 2008).

Greater surface source water fecal contamination is a serious threat to public health. Waterborne disease outbreaks have historically been associated with sustained and heavy precipitation (Curriero *et al.,* 2001; Thomas *et al.,* 2006). Precipitation and snowmelt can generate highly turbid and pathogen rich surface runoff, which degrades surface source water quality (Kistermann *et al.,* 2002). Water treatment systems receiving raw water with high turbidity and pathogen concentration are less likely to maintain the necessary levels of efficiency required to ensure that treated water is pathogen free (Perdek *et al.,* 2003). Variability in source water quality is a large burden on Canadian public health (e.g. Aramini *et al.,* 2000; O'Connor, 2002a; Edge *et al.,* 2008). Potential increases in the level of source water contamination resulting from climate change will need to be anticipated and mitigated in order to prevent the current burden of waterborne disease from increasing (Charron *et al.,* 2004; Delpla *et al.,* 2009).

Historical climate change in Canada over the last century has yet to increase precipitation in proportion to the warming observed. Winter temperatures increased by 1.8^0C and summer temperatures by 1.2^0C in southern BC from 1895 to 1995 (Fraser, 2002). The Clausius Clapeyron equation suggests that the total amount of water in the atmosphere should increase at a rate of 7% per degree Kelvin of surface warming. This ought to result in a corresponding ~7% rise in precipitation driven by moisture convergence (Allan and Soden, 2008). Over the last century, however, total precipitation in Canada, including BC, increased only slightly (Zhang *et al.,* 2001). This increase was less than would be expected given the relationship between temperature and atmospheric moisture. The mitigated response was attributed to a time lag in the climate system, which suggests that precipitation in the region may increase more dramatically in the near future. Projections of such an increase are supported by global satellite observations of precipitation increasing at the same rate as atmospheric moisture over the past two decades (Wentz *et al.,* 2007). As a result, precipitation levels in BC are likely to increase by at least the 20-30% by 2100 projection provided by climate models (Bates *et al.,* 2008).

In order to examine the influence of low frequency hydro-meteorological variability on surface water fecal contamination, some studies have utilized the extreme hydro-meteorological conditions associated with the El Niño climate pattern. Chigbu *et al.* (2004) observed a significant positive correlation between inter-annual rainfall and fecal contamination within the Mississippi Sound in the Gulf of Mexico. Fecal contamination was greatest during El Niño years (associated with high precipitation) and lowest during La Niña (associated with low precipitation). Lipp *et al.* (2001b) observed similar trends in Tampa Bay, Florida, where increased FC concentration was associated with high rainfall during strong El Niño winters.

El Niño episodes in Canada are generally associated with reduced precipitation and river discharge and higher temperatures, which trigger earlier snowmelt. These impacts are not consistent as precipitation anomalies are spatially highly variable and differ in extent from one event to the next. El Niño impacts tend to be greater in the interior of BC than on the coast and strongest during winter (Shabbar *et al.,* 1997). Environment Canada (2010) reported that the El Niño event of 2002-2003 increased mean temperatures by 2^0C and reduced winter precipitation by 50-60% in southeast BC and 10-30% in southwest BC. These anomalies provide an opportunity to examine the response of FC variability to climate variability within BC.

5.1.1 Objectives

This study aims to quantify the relationship between inter-annual FC concentration and hydro-meteorological variability, utilising the high annual hydro-meteorological variability in BC that results from the temperate climate and the influence of the EL Niño and Pacific Decadal Oscillation climate patterns (Manuta and Hare, 2002; Lorenzo *et al.,* 2010). Seasonal FC and hydro-meteorological anomalies are examined to identify the seasons of highest risk of increased fecal contamination. The prevalence of these associations is used to assess the capacity of climate change to influence the total amount of surface source water fecal contamination.

5.2 Data analysis and statistics

Sites for this study were selected from the data set described in chapter 2 on the basis of having a minimum of seven consecutive years of data. Years were defined as beginning in September and ending in August the following year. This was to account for the fact that temperature and precipitation during fall and winter of the preceding year determine the amount of snowmelt the following spring and/or summer. Annual mean FC concentration, rainfall, and river discharge values were calculated and a One-way ANOVA applied to test the significance of variability between years.

Three distinct measures of inter-annual variability were applied to the data to examine associations between inter-annual hydro-meteorological and FC variability.

1) Long-term variability: Time series decomposition was performed using R statistical software and mean monthly values in order to provide equally spaced points in time so as to obtain annual and long-term trends, and the remaining residuals. The relationships between differences in consecutive values of the long-term trend of FC and the long term trend of rainfall and river discharge were examined using a Spearman's rank correlation test.

2) Annual and seasonal anomalies: The significance of associations between FC concentration and hydro-meteorological annual and seasonal deviations from the inter-annual mean were tested using Pearson's product-moment and Spearman's rank tests. Pearson's product-moment test was applied in the case of normally distributed data, determined by the Shapiro-Wilk normality test ($\alpha=0.05$). Spearman's rank test was applied when data were non-parametric.

3) The influence of El Niño: The deviation of seasonal FC concentration and hydro-meteorological parameter values during the El Niño event of 2002/03 relative to neutral, non-El Niño, years was calculated for each site.

All data handling, graphics, and statistical analysis were performed using the statistical software *R* (R Development Core Team, 2009).

5.3 Results

5.3.1 Annual variability

Geometric mean annual FC concentration varied significantly at ten of the nineteen (53%) sites analyzed (significance determined by One-way ANOVA with $\alpha=0.05$, Table 5.3.1). The lowest annual values were most frequent in 2002/03 (32%), and the highest annual values most frequent in the year 2005/06 (58%) (Table 5.3.2). Mean annual river discharge values differed significantly at six of the nineteen (32%) sites analyzed (Table 5.3.1). The lowest annual values were most frequent in 2000/01 (53%) and the highest annual values most frequent in 2005/06 (26%) (Table 5.3.2). Differences in mean annual rainfall values were not significant and the frequency of minimum and maximum values in each year were fairly evenly distributed (Tables 5.3.1 and 5.3.2). Annual variability in mean temperatures were not significant, but 2000/01 was the predominant year with lowest mean temperatures (58%) and 2002/03 the year with highest mean temperatures (37%) (Appendix 3).

Table 5.3.1 Site name and number (#), total sample number (n), and summary statistics of mean, standard error (SE), and range of mean annual fecal coliform, river discharge, and rainfall values for the 19 sites included in the study. Differences between years were assessed by a One-way ANOVA.

Site name	Site #	Total n	Fecal coliform Annual mean, SE, and range (CFU 100ml^{-1})	ANOVA p-value	River discharge Annual mean, SE, and range (m^3 sec^{-1})	ANOVA p-value	Rainfall Annual mean, SE, and range (mm)	ANOVA p-value
Columbia River at Birchbank	7	186	1.64±0.2 (1.21-2.64)	0.022	1886.9±65.8 (1565.36-2056.15)	0.03	1.35±0.15 (0.89-1.95)	0.93
Cowichan River	10	199	10.23±1.3 (5.69-15.01)	0.27	50.22±3.52 (37.72-64.21)	0.24	3±0.73 (1.06-6.6)	0.44
Elk river at Hway 93	11	126	3.19±0.31 (2.41-4.67)	0.28	22.31±4.04 (4.78-36.94)	<0.001	0.65±0.38 (0-2.85)	0.1
Fraser River at Hope	15	164	18.68±4.1 (10.55-41.77)	<0.001	4.66±0.08 (4.29-4.96)	0.67	13.53±1.52 (7.14-19.33)	0.16
Fraser River at Marguerite	16	124	74.55±44.84 (9.85-339.06)	<0.001	1506.4±109.39 (1196.04-1898)	0.069	2.63±0.45 (0.68-4.34)	0.31
Fraser River at Red pass	17	147	1.16±0.07 (1-1.51)	0.19	39.19±2.63 (26.27-45.81)	0.97	2.07±0.42 (0.91-3.58)	0.18
Kettle River at Carson	18	162	5.16±0.87 (3.42-9.98)	0.7	79.49±10.37 (33.36-113.36)	0.25	3.43±0.4 (1.82-4.31)	0.44
Kettle River at Midway	19	172	8.33±1.23 (5.56-14.54)	0.094	43.91±3.52 (30.4-58.55)	0.57	2.71±0.39 (1.89-4.58)	0.18
Koksilah River at Highway 1	20	199	18.99±2.61 (12.1-28.68)	0.04	9.26±1.02 (6.39-15.04)	0.24	2.98±0.74 (1.01-6.6)	0.48
Kootenay River at Creston	21	163	3.44±0.7 (1.86-6.83)	0.04	147.22±11.8 (93.2-186.11)	0.52	4.11±0.24 (3.15-4.86)	0.76
Kootenay River at Fenwick	22	134	3.12±0.59 (1.7-6.35)	0.27	148.84±20.47 (70.87-199.66)	0.55	2.14±0.36 (1.07-3.6)	0.17
Nechako River	27	170	4.75±0.41 (3.24-6.65)	0.26	233.95±16.07 (191.12-295.38)	0.26	3.65±0.67 (1.74-7.18)	0.18
Okanagan River at Oliver	30	171	6.55±0.68 (4.72-9.58)	0.59	14.6±2.19 (7.9-20.06)	<0.001	1.76±0.3 (0.5-2.68)	0.55
Peace River	31	135	3.43±0.6 (1.68-5.95)	0.007	1507.12±82.36 (1105.89-1795)	0.002	2.51±0.64 (0.09-4.73)	0.41
Salmon river at Salmon Arm	36	2557	72.32±4.89 (57.4-95.53)	<0.001	4.44±0.52 (2.6-6.22)	<0.001	1.1±0.06 (0.89-1.36)	0.96
Similkameen River at Princeton	39	186	2.28±0.18 (1.83-3.22)	0.33	19.77±2.98 (9.74-30.88)	0.1	1.7±0.25 (1.24-2.91)	0.2
Similkameen River at US boarder	40	158	4.21±0.82 (1-8.09)	0.016	38.64±4.74 (20.45-51.82)	0.098	1.73±0.4 (0.5-3.26)	0.42
Sooke Lake	41	222	1.27±0.4 (0-2.99)	0.02	1.12±0.28 (0.38-2.06)	0.02	2.25±0.46 (0.11-3.27)	0.23
Thompson River	43	154	2.81±0.41 (1.75-4.72)	0.01	682.6±84.27 (233.5-948.09)	0.052	1.48±0.29 (0-2.61)	0.16

Table 5.3.2 Percentage of sites with maximum (Max) or minimum (Min) annual mean fecal coliform, river discharge, rainfall, and temperature values in each year.

Year	Fecal coliform		River discharge		Rainfall		Temperature	
	Min	Max	Min	Max	Min	Max	Min	Max
2000/01	26	11	53	5	21	0	58	5
2001/02	26	16	21	21	32	16	32	0
2002/03	32	0	11	11	11	16	0	37
2003/04	16	0	11	21	5	21	5	26
2004/05	0	16	0	16	11	37	0	11
2005/06	0	58	5	26	21	11	5	21

5.3.2 Long-term fecal coliform and hydro-meteorological variability

Long-term FC variability was significantly correlated with river discharge and rainfall variability at 47% of the sites. Correlation between long-term FC concentration and river discharge variability was more frequent (8/19 sites, mean Spearman's correlation: ρ = 0.51±0.06) than correlation between FC and rainfall (3/19 sites, mean Spearman's correlation: ρ = 0.45±0.1) (Table 5.3.3). Long-term trends in FC concentration and river discharge variability showed similarities among a number of the sites 10, 18, 22, 36, 39, and 40 (Fig. 5.3.1 panels a, c, d, f, g, and h, respectively). Rainfall and river discharge were associated with FC variability for sites 22 and 31 (Fig. 5.3.1 panels d and j, for site 22, and panels e and k, for site 31).

Table 5.3.3 Spearman's rank correlation coefficient (ρ) for long-term (L-T) trend in fecal coliform (FC) variability in relation to long-term river discharge and rainfall variability.

Site name	Site no.	L-T FC ~ River discharge		L-T FC ~ Rainfall	
		Spearman's ρ	p-value	Spearman's ρ	p-value
Cowichan River	10	0.27	0.01	-	-
Fraser River at Hope	15	0.63	<0.001	-	-
Kettle River at Carson	18	0.71	<0.001	-	-
Kootenay River at Creston	21	-	-	0.43	<0.001
Kootenay River at Fenwick	22	0.35	0.01	0.29	0.01
Peace River	31	0.53	<0.001	0.64	<0.001
Salmon River at Salmon Arm	36	0.36	<0.001	-	-
Similkameen River at Princeton	39	0.59	<0.001	-	-
Similkameen River at US boarder	40	0.64	<0.001	-	-

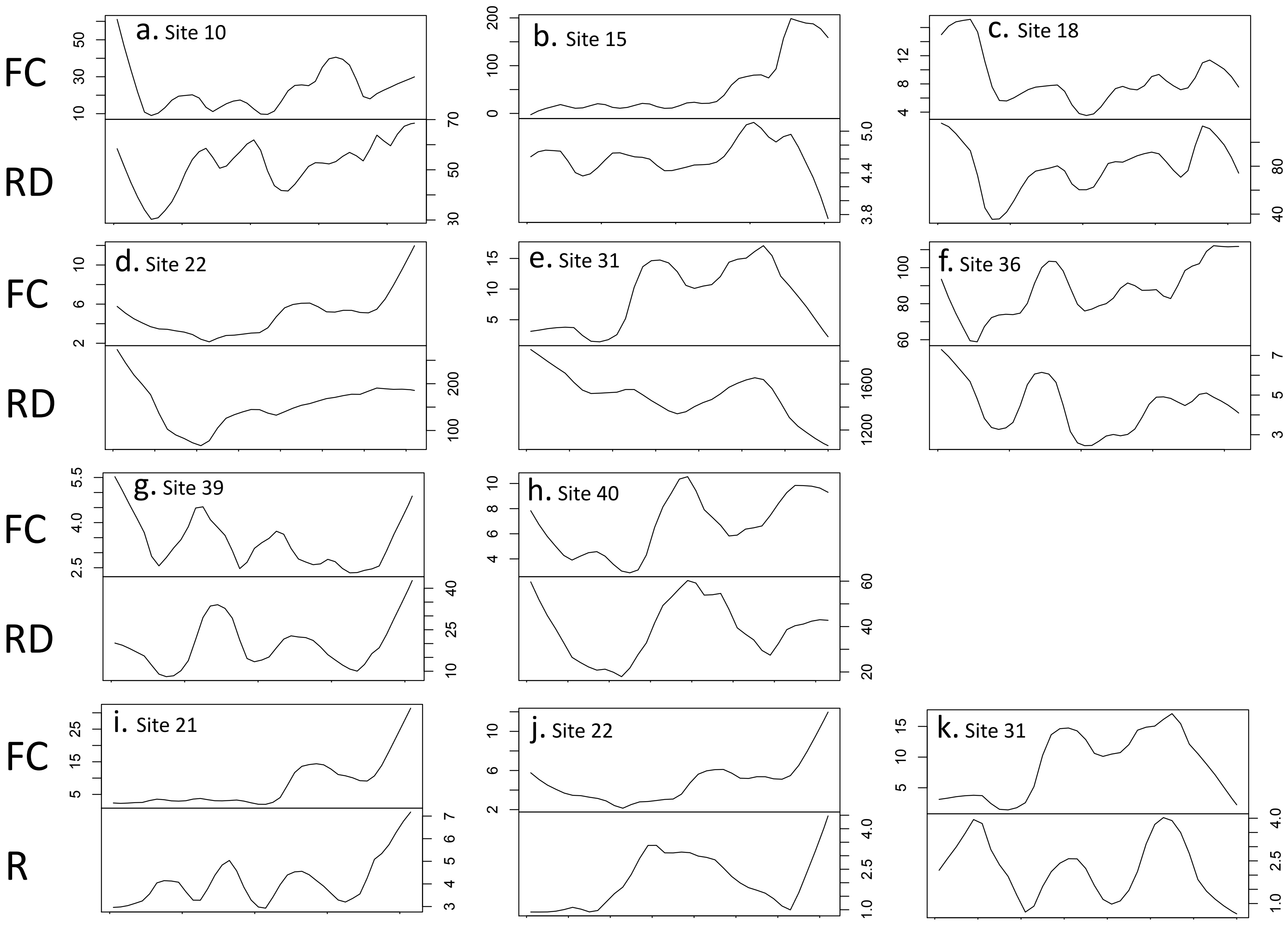

Figure 5.3.1 Time series of long-term variability of fecal coliform (FC (CFU 100ml^{-1})) and river discharge (RD (m^3 sec^{-1})) (upper 3 rows), and fecal coliform and rainfall (R (mm)). The y-axis scale is different between graphs but the x-axis is consistent (Time (2000-2006)).

5.3.3 Fecal coliform and hydro-meteorological anomalies

Annual and seasonal anomalies from the inter-annual mean value for FC concentration, rainfall, and river discharge were calculated. Significant evidence of FC anomalies being correlated with river discharge or rainfall anomalies is shown in Table 5.3.4 (indication of significance was not constrained to α <0.05 as sample size was only 6). Positive correlation between mean annual FC concentration and river discharge anomalies was observed at three sites (7, 20, and 40), spring FC concentration and river discharge anomalies at two sites (11 and 39), and winter FC concentration and river discharge anomalies at three sites (15, 18, and 22). Positive correlations between spring FC concentration and rainfall anomalies were observed at site 11, and winter FC concentration and rainfall anomalies at sites 10 and 15 (Table 5.3.4). The only temperature anomalies associated with rainfall anomalies, which appeared to drive FC anomalies, occurred at site 10 (Pearson's correlation for temperature and FC anomalies = 0.95, p = 0.004).

Table 5.3.4 Pearson's product-moment (Test = P) and Spearman's rank correlation coefficient (Test = S) test results for mean annual and seasonal fecal coliform (FC) anomalies that were correlated with river discharge and rainfall anomalies from the inter-annual (IA) mean.

Site name	Site no.	IA anomaly FC ~ River discharge				IA anomaly FC ~ Rainfall			
		Period	Test	Correlation	p-value	Period	Test	Correlation	p-value
Columbia River at Birchbank	7	year	P	0.85	0.03	-	-	-	-
Koksilah River at Highway 1	20	year	P	0.88	0.02	-	-	-	-
Similkameen River at US boarder	40	year	P	0.92	0.01	-	-	-	-
Elk river at Hway 93	11	spring	P	0.87	0.02	spring	P	0.80	0.06
Similkameen River at Princeton	39	spring	P	0.72	0.11	-	-	-	-
Cowichan River	10	winter	P	-	-	winter	P	0.73	0.10
Fraser River at Hope	15	winter	S	0.77	0.10	winter	S	1.00	0.00
Kettle River at Carson	18	winter	S	0.81	0.05	-	-	-	-
Kootenay River at Fenwick	22	winter	S	0.85	0.03	-	-	-	-

Years in which anomalies were positive or negative varied among sites. Sites 20 and 18 had positive anomalies in 2001/02 and 2004/05 and negative anomalies in 2000/01, 2002/03, 2003/04, and 2005/06 (Fig. 5.3.2, panels b and e). Site 39 had a similar trend to sites 20 and 18, but experienced positive anomalies in 2003/04 and 2005/06 (Fig. 5.3.2, panel d). Sites 7, 40, 22, 11, and 15 are characterized by a trend of negative anomalies for the first three years of data followed by positive anomalies for the latter two or three years (Fig. 5.3.2, panels a, c, f, g, and h). These sites experienced an increase in river discharge and FC concentration over the period covered by the data. Site 10 anomalies conform to neither of the aforementioned trends, increasing from 2000/01 to 2002/03 and declining thereafter. Site 10 was the only site in which rainfall seems to be the primary driver of FC anomalies (Fig. 5.3.2 i).

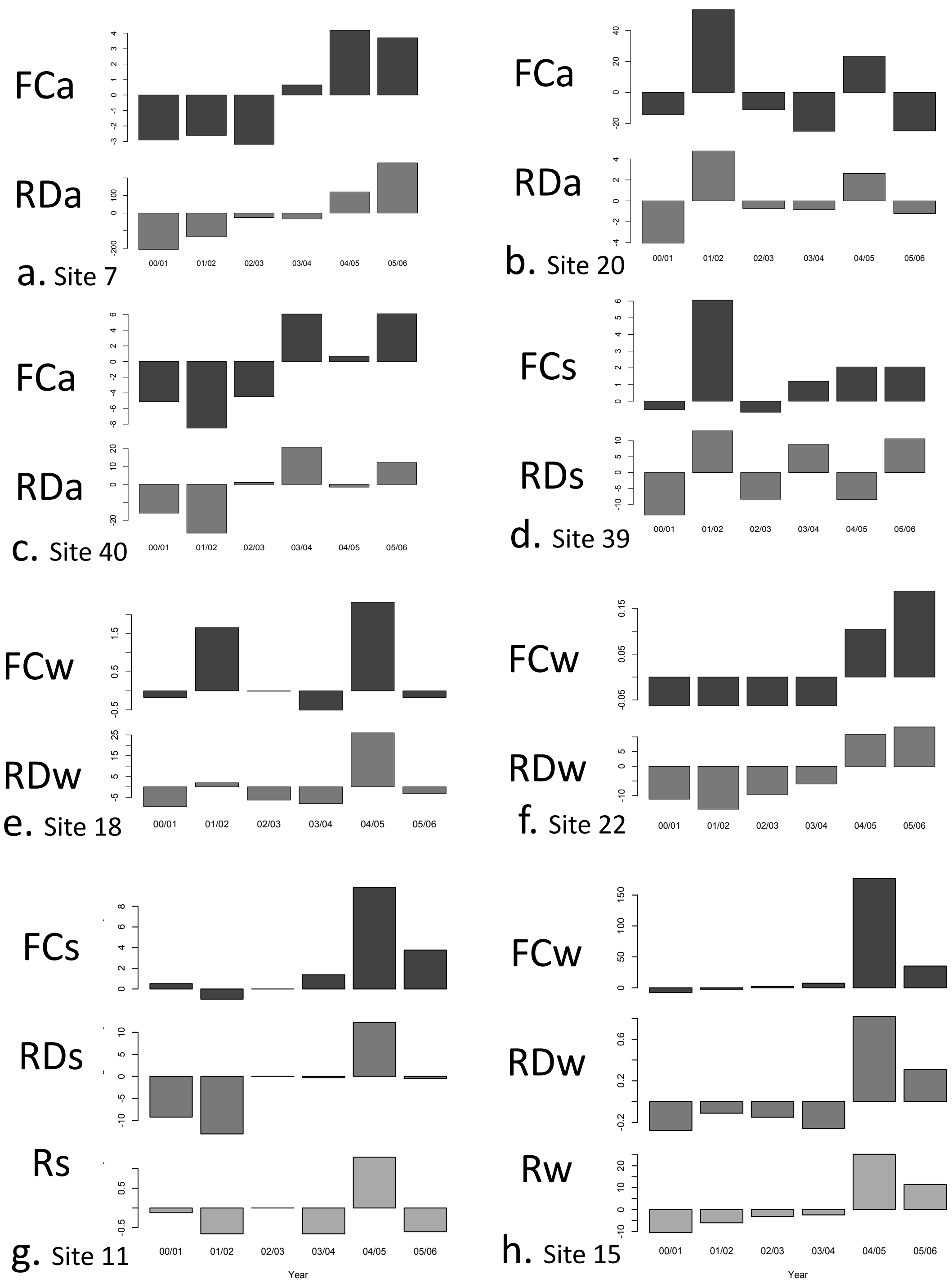

Figure 5.3.2 remainder of figure and figure title on following page

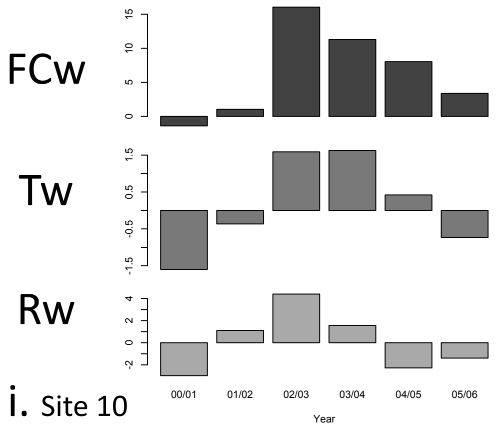

Figure 5.3.2 Mean annual and seasonal fecal coliform, river discharge, rainfall, and temperature deviations from the inter-annual mean for sites (a=annual; w=winter; s=spring, site number adjacent to plot label) where fecal coliform (FC (CFU $100ml^{-1}$)) anomalies were significantly correlated with river discharge (RD (m^3 sec^{-1})), rainfall (R (mm)), and/or temperature (T (^{0}C)) anomalies. Y-axis scales differ among graphs, but x-axis categories are consistent among graphs (years from 2000/01 to 2005/06). See table 5.3.4 for site names.

5.3.4 The impact of the 2002/03 El Niño event

During the 2002/03 El Niño event, seasonal FC concentration and river discharge values tended to be lower than in neutral (non-El Niño) years, whereas temperature and rainfall values were both positive and negative. Mean seasonal FC concentration was 13±5% lower than neutral years, mostly occurring during spring and summer, with little if any deviation in fall and winter. Mean seasonal temperatures were similar to neutral years, except in winter when they were 65±31% lower. Mean seasonal rainfall tended to be higher than in neutral years (16±17%) with the exception of summer, when it was 35±17% lower. Mean river discharge levels were consistently lower than in neutral years, with a mean negative annual deviation of 15±2% (Fig 5.3.3).

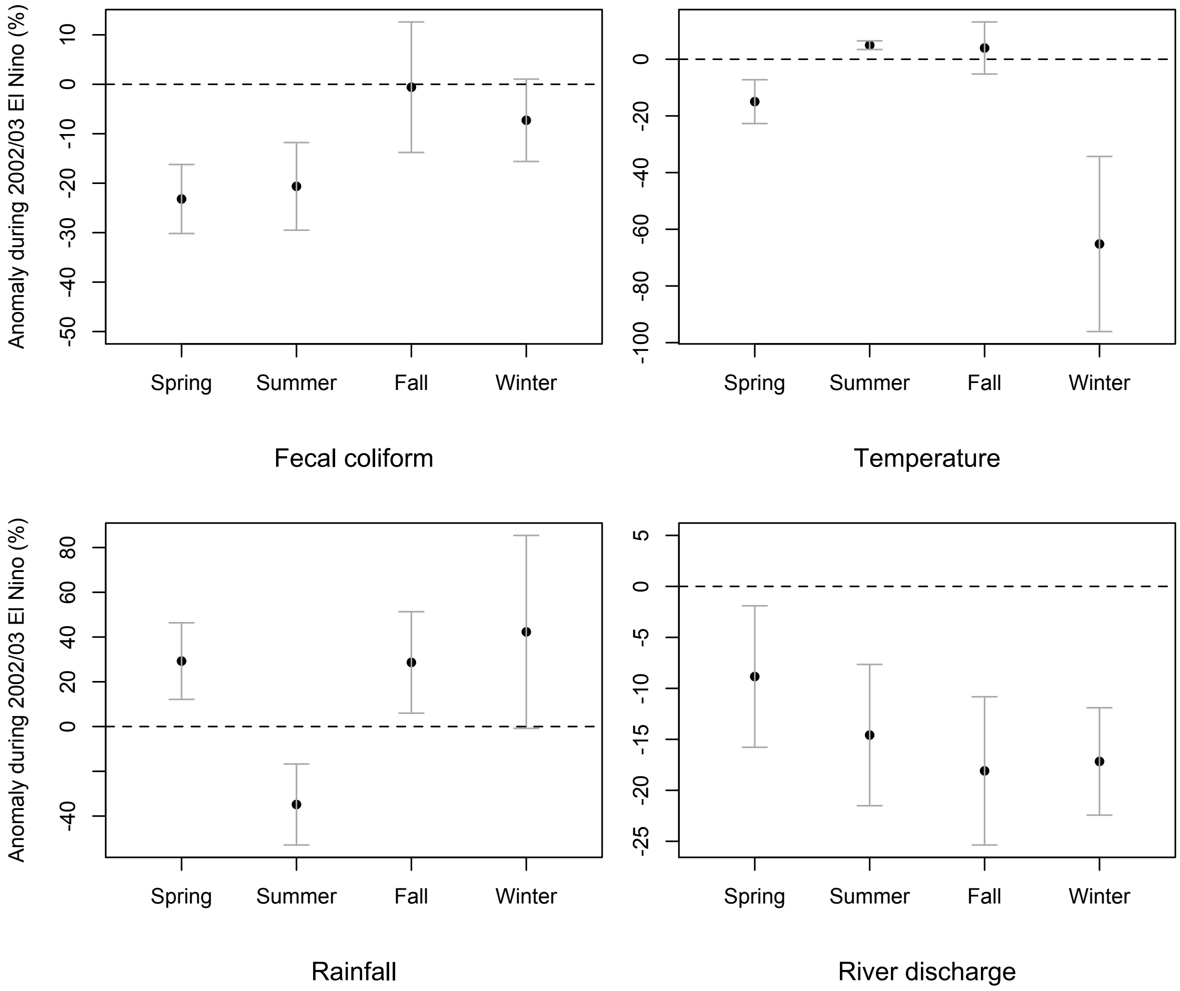

Figure 5.3.3 The deviation of seasonal FC and hydro-meteorological parameter values during the El Niño event of 2002/03 relative to neutral years, shown by the dashed horizontal line. Solid circles show the mean of all 19 sites and whiskers show the standard error of the mean.

5.4 Discussion

Annual FC variability in surface water was significantly associated with hydro-meteorological variability for 58% of the sites examined. Significant associations between FC variability and river discharge were more frequent than those between FC variability and rainfall for long-term variability, annual and seasonal anomalies, and deviations during the 2002/03 El Niño. Associations between rainfall and FC concentration were observed at five sites that, with the exception of the Peace River site, are all located along the southern boarder of BC where warmer temperatures are likely to have increased the influence of rainfall-induced surface runoff on FC transport into surface water.

The greater prevalence of river discharge than rainfall impacts on FC variability is likely due to the majority of watersheds in the study (15 out of 19) having SD runoff regimes. The majority of surface runoff in these watersheds is generated by snowmelt, which strongly determines river discharge variability (WDFW, 2011). The volume of snowmelt generated in spring is dependant on the amount of snowpack accumulation the previous winter. Greater than average volumes of snowmelt-induced surface runoff, indicated by greater than average river discharge, is likely to increase the transport of fecal contaminants into surface water (Dorner *et al.,* 2006 and 2007). This mechanism would account for the associations observed between FC and river discharge variability. Rainfall-induced runoff is also capable of raising fecal contamination levels in surface water (Kay *et al.,* 2008). However, a truly representative estimate of the influence of rainfall on inter-annual surface water fecal contamination would require analysis of a greater number of RD watersheds than were available in this study.

5.4.1 Long-term fecal coliform and hydro-meteorological trends

The significant associations observed between long-term FC concentration and hydro-meteorological trends indicate that changes in total precipitation can generate corresponding fluctuations in surface water fecal contamination on an inter-annual time scale. Lipp *et al.* (2001a) observed similar associations between years with higher precipitation and fecal contamination within the Charlotte Harbour estuary in Florida. Precipitation was thought to increase soil saturation and generate greater surface runoff that carried fecal waste, primarily from failing septic systems, into the estuary. Dorner *et al.* (2006) demonstrated the ability of surface runoff to greatly increase FC loading using a watershed-scale pathogen fate and transport model. This was confirmed by field observations of rapidly increasing FC concentration in surface water by one or two orders of magnitude during precipitation events (Dorner *et al.,* 2007). The influence of snowmelt and rainfall-induced runoff on fecal contaminant transport into surface water is likely to have driven the positive associations observed in this study.

Associations between similar FC concentration and hydro-meteorological long-term trends were observed over large spatial and temporal scales. Sites with similar FC concentration and river discharge trends (sites 10, 18, 22, 36, 39, and 40) demonstrate the capacity for long-term regional precipitation variability to have analogous and simultaneous impacts on FC variability among a number of watersheds. Previous studies have shown the capacity of single hydro-meteorological events to greatly increase FC concentrations (Kistermann *et al.,* 2002). Attempts to examine longer-term interactions, however, have failed to identify consistent or robust functional relationships (Schaffter and Parriaux, 2002; Schaffter *et al.,* 2004; Signor *et al.,* 2005; Wilkes *et al.,* 2009). Therefore, much of the uncertainty associated with the impact of climate change on surface water fecal contamination pertains to the response of contamination levels to changes in total precipitation on seasonal and annual time scales. Strong associations between FC concentration and hydro-meteorological variability over a six-year period across a large geographical area demonstrates the capacity of increased precipitation to drive a sustained increase in surface water fecal contamination.

5.4.2 Fecal coliform and hydro-meteorological anomalies

Variability in total annual and seasonal rainfall and river discharge appeared to drive similar variability in surface water FC concentrations in half of the watersheds examined in this study. Similar results produced by examining anomalies and long-term trends, such as which sites showed significant associations between hydro-meteorological and FC concentration and the predominance of river discharge associations with FC concentration over rainfall, provide support for the inferred influence of rainfall and river discharge driving long-term changes in surface water fecal contamination. Each method has particular advantages. The use of time series decomposition to obtain the long-term trend provided a higher resolution of long-term variability (~80 data points per site, as long-term trend was calculated from the monthly as opposed to annual mean, which only provided 6 data points per site), whereas calculating anomalies provided the opportunity to identify individual seasonal and annual associations. Regardless of the method used, increases in rainfall and river discharge were consistently seen to be associated with greater fecal contamination among certain sites.

Associations between anomalies suggest that greater precipitation in the study region will influence fecal contamination levels to the greatest extent in spring and winter. Inter-annual relationships between FC concentration and hydro-meteorological variability were observed in annual, winter, and spring deviations from the inter-annual mean but not in summer or fall deviations from the inter-annual mean. Spring rainfall and river discharge anomalies at site 11, Elk River, appeared to cause corresponding FC anomalies. A study of FC concentration variability within the Grand River watershed in Ontario observed an increase in spring FC concentrations concurrent with increasing rainfall (Dorner *et al.,* 2007). The anomalies at site 11 illustrate that this relationship extends to the magnitude of rainfall-induced runoff, which can alter the total amount of surface water fecal contamination.

A number of sites (10, 15, 18, and 22) showed positive associations between river discharge volumes and FC concentration in winter. These results match those of Chigbu *et al.* (2004) who observed a positive relationship between increased winter river discharge in the Pearl River and the FC concentration within the Mississippi Sound in the Gulf of Mexico. The Pearl River watershed is more analogous to the watersheds of sites 10 and 15, which are rainfall-dominant and experience greater rainfall during the winter, than those of sites 18 and 22, which are snowmelt-dominant. As a result, wetter winters for sites 10 and 15 are likely to result in greater than average peak FC concentrations, whereas FC concentrations are typically low during winter for sites 18 and 22 and, therefore, increases in FC concentration during this season do not pose such a high risk.

Greater mean winter rainfall at site 10, the Cowichan River, appeared to drive an increase in FC concentration. The proportion of winter precipitation that fell as rain was positively related to temperature. The relationship between temperature, rainfall-induced runoff, and surface water fecal contamination suggests that projected increases in winter temperatures will amplify the amount of fecal contamination transported into the Cowichan River, and those with similar hydro-meteorological characteristics (Bates *et al.,* 2008).

5.4.3 The impact of the 2002/03 El Niño event

Seasonal deviations in hydro-meteorological parameters due to the 2002/03 El Niño event were variable among sites. Associations between mean river discharge and

FC deviations in spring and summer, however, provided evidence of reduced FC transport in response to lower winter precipitation. Deviations for this study did not resemble those reported by Environment Canada (2010) as they were calculated from only six years of data and not the thirty-year climate norm. As a result, temperature anomalies were fairly insignificant; except for the negative anomaly observed in winter. Positive rainfall anomalies tended to occur in fall, winter, and spring, potentially due to warmer temperatures. Negative river discharge anomalies in every season reflected the reduction in precipitation levels associated with the El Niño event (Environment Canada, 2010).

Evidence of negative FC anomalies in response to reduced precipitation was strong in the spring and summer, but weak in the fall and winter. Positive rainfall deviations in the fall, winter, and spring were not reflected in river discharge levels, which were 17% below the inter-annual mean. This indicates that rainfall had little influence on surface runoff levels, which would account for the lack of evidence for associations between rainfall and FC anomalies. Negative FC anomalies in spring and summer (-22%) corresponded with negative river discharge anomalies (-12%). This association likely arose due to a reduction in snowmelt-induced runoff and fecal contaminant transport into surface water (Kistermann *et al.,* 2002; Dorner *et al.*, 2007; Kay *et al.,* 2008). Negative FC deviations in summer are likely to have been enhanced by lower than average rainfall-induced runoff. The lack of evidence for FC concentration being influenced by fall and winter deviations in river discharge and rainfall is to be expected given the high proportion of sites that were SD (15 out of 19) and therefore experienced negligible FC transport and variability during these seasons.

Hydro-meteorological associations with FC variability during the El Niño event paralleled those seen by Lipp *et al.* (2001b) and Chigbu *et al.* (2004) in coastal marine water within the Gulf of Mexico. In Tampa Bay, Florida, FC concentrations were 16.2% to 45.5% lower during La Niña events, which experienced similar precipitation and river discharge anomalies as those seen during the 2002/03 El Niño in BC (Lipp *et al.,* 2001b). As with the current study, however, variability between sites and seasons was high. Anomalies for all parameters tended to be more significant during winter and FC anomalies ranged from strongly negative to positive among sites during the same event (Lipp *et al.*, 2001b). These associations were supported by a similar study in the Mississippi Sound. Low rainfall and river discharge during the 1999-2000 La Niña event were associated with the lowest winter FC concentration among 11 years of data (Chigbu *et al.*, 2004). These studies support the hypothesis that annual variability in mean precipitation will drive similar variability in mean FC concentration. The impact of this association in the Gulf of Mexico was greater during the winter, in contrast to the greater impact observed in spring and summer in this study, suggesting that the period of increased risk of source water contamination during years of greater precipitation is related to hydro-climatic regime.

5.4.4 Synthesis of results

Although strong associations between inter-annual FC concentration and hydro-meteorological variability were observed within a number of watersheds (11), a similar proportion (8) failed to demonstrate any evidence of such associations. Among those watersheds where mean annual and seasonal surface water FC concentration was related to rainfall and river discharge, associations were observed during different seasons, even among watersheds with similar runoff regimes. This type of variability among sites is typical of observations made by previous studies. A study conducted by Wilkes *et al.* (2009) within the South Nation watershed in Ontario, Canada, found associations between FC concentration and rainfall variability to be fairly weak and variable but most frequent during spring and summer. Associations between FC concentration and river discharge were also fairly weak and variable, but most frequently observed during fall and winter. Wilkes *et al.* (2009) concluded that generalizations on the influence of increased precipitation on surface water FC concentration could not be made. Similarly, Schaffter *et al.* (2004) were unable to make any general conclusions about the relationship between the presence of waterborne pathogens and hydro-meteorological conditions within a mountainous watershed in the west of Switzerland.

High variability observed in the association between hydro-meteorological and FC variability in this study affirm the evidence that basic relationships between precipitation and FC concentration cannot be meaningfully applied across different watersheds to predict the future FC concentration of surface water. The aim and scope of this study, however, was to assess the potential for climate change to influence surface water fecal contamination. The significant correlation between inter-annual FC concentration and hydro-meteorological variability evidenced by the majority of sites provides strong evidence that projected rainfall and snowmelt variability due to climate change will influence surface water fecal contamination. The strong correlation between long-term FC concentration and hydro-meteorological trends for some sites suggests that models may be effective at providing estimates of the magnitude with which FC concentration will change (Zhu *et al.,* 2011). The influence of climate change will vary among watersheds due to the unique combination of climate and land-use factors that influence FC transport and survival at each site (Ferguson, 2003a). This necessitates the need to assess the risk posed to source water sites on an individual basis, although general land-use and climate characteristics should be used as indicators to consider the magnitude and timing of contamination risks.

5.5 Conclusions

Increased annual and seasonal rainfall and river discharge were positively associated with surface water FC concentration for 58% (11 out of 19) of the sites examined. River discharge was more frequently associated with long-term FC variability, which, in many cases, indicated the greater influence of snowmelt than rainfall on mean FC concentration. This was to be expected given that the majority of watersheds (15 out of 19) examined had SD runoff regimes. The capacity of long-term hydro-meteorological trends to influence FC trends was attributed to the mechanism of snowmelt and rainfall-induced runoff transporting more fecal contaminants into surface water. This explains the influence of annual hydro-meteorological variability on FC concentration in winter, the season of greatest precipitation, and spring, the season of greatest snowmelt, but not in summer or fall. Warmer temperatures in winter were associated with greater rainfall, which appeared to drive a corresponding increase in mean FC concentration in the Cowichan River, a RD watershed on the southern end of Vancouver Island. Given that winter temperatures are projected to rise and runoff regimes to shift towards greater rainfall dominance, similar impacts are likely to occur across BC over the coming century.

The El Niño event in 2002/03 provided further evidence of inter-annual precipitation variability influencing FC concentration. A mean reduction in river discharge during spring and summer following the El Niño event was associated with a mean reduction in FC concentration among all the sites in the study. Rainfall appeared to have little influence on FC concentration, but may have contributed to the negative FC deviations observed in summer, by means of less rainfall-induced runoff to transport fecal contaminants. Lower river discharge and higher rainfall did not appear to influence FC concentration during fall and winter, which can be attributed to the predominance of SD runoff regimes among the watersheds.

The capacity of precipitation events to increase fecal contaminant loading into surface water has been well demonstrated. This study presents the first evidence that such interactions occur over a long-term, inter-annual, time frame. This demonstrates the capacity for changes in the total amount of seasonal and annual precipitation to cause corresponding changes in the total annual and seasonal amount of surface water fecal contamination.

Chapter 6 Synthesis and interpretation of results

This water quality study was conducted to assess the capacity for changes in land-use and climate to influence surface water fecal contamination. Differences in FC concentration and variability among watersheds were significantly related to land-use, specifically agriculture and urban land. Rainfall and snowmelt-induced surface runoff and subsurface flow was shown to influence both seasonal patterns and the total amount of surface water fecal contamination within watersheds. Land-use can influence surface water fecal contamination by altering the presence of fecal contaminants and surface hydrology within a watershed. Given that these land-use impacts interact with hydro-meteorological variability in a complex manner to influence surface water fecal contamination, it is highly improbable that surface water fecal contamination levels will respond to climate change impacts consistently within and among watersheds. This research was premised on the idea that general basic relationships characterize the influence of hydro-meteorological and land-use factors on surface water FC concentration among watersheds with similar climate variability and land-use composition. To some degree this proved to be true, although in each case a significant number of sites failed to show evidence for such relationships. Quantifying this variability is important. Significant associations between hydro-meteorological and FC variability were observed for around half of the cases examined. This indicates that the probability of climate change influencing surface water fecal contamination at any given surface water location within the study area of southern BC appears to be roughly even.

Anthropogenic land-use impact among watersheds continues to increase as a result of expanding urban development and intensification of agriculture. These activities are generally associated with an increase in the production of fecal waste by host organisms of enteric pathogens. In response, some large municipalities in BC have purchased whole watersheds, which are then protected to limit selected activities, sometimes even to the point of removing wildlife of concern. This helps to minimise fecal contamination in the watershed and improves the quality of drinking water produced from source water within the watershed. However, this approach may not be financially viable for smaller communities or may not be possible for more developed regions. In such cases, an increase in anthropogenic activity presents a serious threat to source water quality by elevating the amount of fecal waste available to contaminate surface water.

The risk associated with anthropogenic land-use was identified by positive relationships between the extent of agricultural and urban land-use in watersheds and their downstream FC concentration. A comprehensive list of 17 land-use types was used to identify those most dominant in determining surface water FC variability among watersheds. Fecal coliform concentration was primarily influenced by the proportion of agriculture, and secondarily by urban land-use in the more highly contaminated watersheds. This demonstrates that activities and modifications to the landscape associated with these land-use types are a major source of fecal contamination impairing source water quality. Previous studies have often made qualitative observations of the presence of urban or agricultural land being associated with higher downstream FC concentrations (Kistermann *et al.,* 2002; Dorner *et al.,* 2007). This study provides quantitative evidence from 43 watersheds demonstrating that surface water contamination from diffuse sources is principally derived from agriculture among certain watersheds and that very high contamination can occur due to the synergistic influence of high agricultural and urban development.

The proportion of agricultural land-use within each watershed was used as an indicator of anthropogenic impact to examine the risk to source water quality associated with increasing development. Land-use had a strong and positive log-linear relationship with mean FC concentration within two different sub-sets of sites, Group 1 and Group 2 ($r^2 = 0.90$, $p < 0.001$ and $r^2 = 0.84$, $p < 0.001$, respectively). These groups were categorized by greater baseline FC concentrations observed in Group 2 than Group 1, potentially due to warmer temperatures and lower river discharge. This demonstrates that watersheds with existing fecal contamination from point sources are especially vulnerable to source water degradation resulting from agricultural development. Kay *et al.* (2008) observed that the proportion of improved pasture could account for 42% of the variability in mean FC concentration among watersheds throughout the UK. Fecal coliform concentration was determined from relatively few data points (15-40) obtained over a short period of 6-8 weeks (Kay *et al.,* 2008). The long sampling period of 4-7 years and relatively large sample number utilized in this study may account for the unprecedented strength of relationship between agricultural land and FC concentration observed among Group 1 and Group 2 sites.

Previous work supports the observation that the proportion of agricultural land is the most robust land-use indicator of surface water fecal contamination. Layuatey *et al.* (2007) measured the nearest distance of 7 different sources of fecal waste to their sampling location to examine their relative predictive power in determining the presence or absence of *Listeria monocytogenes* within the South Nation River watershed, Ontario.

The proportion of cropland in the watershed, however, was a better predictor than the alternative measures of land-use impact. Other land-use factors, such as the proximity of sources of fecal contaminants to surface water, may help to explain the variability observed among the different sub-sets of watersheds identified in this study (Fig. 3.3.3). Furthermore, variability in mean FC concentration among sites was also seen to result from additional factors other than land-use composition, such as sewage treatment plants, low dilution in smaller streams, and higher temperatures.

Unexplained variability in the relationship between land-use and FC dynamics among the different sub-sets of sites presents an interesting area for further research. This study was limited to land-use composition data and could not, therefore, control or account for many important variables, such as point sources of contamination, livestock density, riparian vegetation, and best management practices. Of particular interest is the FC variability within the group of sites where FC concentration did not appear to be related to land-use (termed anomalies, Fig. 3.3.3). Fecal coliform concentrations for these sites may have been determined by anthropogenic influences not accounted for in an analysis using only land-use composition. These include the presence and age of storm water and sanitation infrastructure and the density of septic systems and pit latrines within the watershed (Walters *et al.,* 2010). Surveying individual watersheds for such factors and including them in the analysis could help account for unexplained FC variability and provide useful guidance for the mitigation of fecal contamination from such sources.

The influence of anthropogenic land-use on FC parameters is of crucial concern to the production of safe drinking water. Disease causing pathogens in source water must be neutralized by disinfection before it can be safely consumed. Disinfection is compromised by FC and other organic contaminants, therefore, greater concentrations and variability of fecal contamination in source water increases the risk of treatment failure (Perdek *et al.,* 2003). The strong relationship observed between mean FC concentration and anthropogenic land-use indicates the need for robust technology and management of disinfection of source water in watersheds that are impacted by agricultural and urban development. The Group 1 sub-set of sites, in which surface water FC variability was attributed primarily to loading of diffuse fecal contaminants from agricultural land, demonstrated a positive relationship between site FC variance and the proportion of agricultural land-use in the watershed. This indicates that watersheds with greater agricultural activity experience higher fluctuations in surface water fecal contamination. High fluctuations in raw water fecal contamination is challenging to manage. This process was illustrated during the Walkerton waterborne disease outbreak, in 2000, by the association observed between fecal contamination variability and cases of gastrointestinal infection caused by verotoxigenic *E. coli* (O'Connor, 2002b; Greer *et al.,* 2008).

Rainfall and snowmelt-induced runoff has been shown to transport fecal contaminants into surface water from within the surrounding watershed. As a result, periods of high rainfall and river discharge are associated with high FC and turbidity levels in surface water, which increases the risk of water treatment failure (Signor *et al.,* 2005). Water treatment processes must be managed to ensure adequate disinfection during such high-risk periods. A conservative estimate attributed 17,500 physician visits, 85 hospital admissions, and 138 paediatric hospital emergency room visits between 1992 and 1998 in Metro Vancouver to variability in source water quality (Aramini *et al.,* 2000). The ability to anticipate the influence of projected hydro-meteorological variability on surface water fecal contamination presents a valuable tool for the improved management of safe source water. The influence of rainfall on FC variability has tended to be too variable, however, to be able to provide robust predictions (Schaffter and Parriaux, 2002; Schaffter *et al.,* 2004; Signor *et al.,* 2005; Wilkes *et al.,* 2009).

Climate change is altering runoff regimes within watersheds. Changes in seasonal runoff variability may present a challenge to the management of surface source water quality and water treatment. This will depend on the extent to which seasonal variability in surface water fecal contamination is determined by snowmelt and rainfall-induced surface runoff. The influence of rainfall and snowmelt on seasonal FC variability was examined among the 43 watersheds included in this study. Evidence for an association between seasonal FC and hydro-meteorological variability was seen in 18 of the 43 watersheds examined. This suggests that many surface water locations in BC may be unaffected by changes in runoff regime. This proportion is likely a conservative estimate, however, given the challenge of obtaining a truly representative estimate of FC variability from standard sampling regimes (Meays *et al.,* 2006a).

The probability of surface water fecal contamination being influenced by climate change appears to differ in relation to the existing runoff regime of a watershed. Watersheds where surface runoff was principally generated by snowmelt (SD) had a greater proportion of sites with significant hydro-meteorological and FC associations (46%) than those where it was generated by rainfall and snowmelt (RSI) at 43% or principally rainfall (RD) at 22%. Furthermore, associations between seasonal FC and hydro-meteorological variability were stronger for SD watersheds than RSI or RD watersheds (65%, 58%, and 46% of mean monthly FC concentration variance explained, respectively).

Seasonal rainfall variability only appeared to influence FC variability in RD watersheds in which rainfall events consistently induced surface runoff, and thus strongly impacted FC loading and river discharge (explaining >50% variability). Modifications to the landscape and the natural hydrograph can interrupt this relationship, which may have contributed to the low proportion of RD watersheds manifesting evidence of FC variability being related to rainfall (Fraser, 2002; Ferguson, 2003a; Arnone and Walling, 2007). Given these observations, hydro-meteorological influences on seasonal FC variability will tend to occur with greater frequency and consistency in SD watersheds than RD watersheds. This has particular significance given the greater changes that climate change will have on runoff regimes of SD watersheds in comparison to RD watersheds.

Small increases in temperature are associated with major changes in seasonal patterns of runoff within SD watersheds. Warming towards the end of last century increased early spring snowmelt and reduced summer precipitation, causing greater seasonal variability in SD river hydrographs (Fraser, 2002). Results from this study indicate that SD watersheds in which winter temperatures remain below zero will experience peak fecal contamination earlier in the year but see a net decrease of contamination during spring and summer, when it is typically high, due to less snowmelt and rainfall-induced runoff. Furthermore, projected future warming has the capacity to alter the runoff regime of a watershed. Snowmelt-dominant watersheds in this study had mean winter temperatures of around -2.3^0C and were shown to transition into RSI and RD watersheds when the mean winter temperature rose to -1^0C and $>0^0$C respectively. By the end of the 21st century, BC is projected to experience annual mean temperature increases of 1.7^0C to 4^0C and precipitation increases of 20-30%, mostly in winter (Bates *et al.,* 2008; Murdock and Spittlehouse, 2011). The relative influence of snowmelt and rainfall on FC variability was shown to be associated with the proportion of surface runoff generated within a watershed. As a result, SD sites in which winter mean temperatures increase above freezing will begin to experience less fecal contamination concurrent with snowmelt in spring, as snowpack accumulation decreases, and more contamination during fall and winter due to greater rainfall.

Alongside questions as to whether seasonal patterns of fecal contamination will change is the equally crucial question of whether projected increases in precipitation are likely to increase the total seasonal or annual amount of surface water fecal contamination. Two previous studies have investigated this question with regard to coastal marine waters in the Gulf of Mexico and found that years with higher fecal contamination corresponded to years with greater total precipitation (Lipp *et al.,* 2001a; Chigbu *et al.,* 2004). Inter-annual FC variability has not been examined in relation to hydro-meteorological variability in freshwater systems. Previous studies have assessed the influence of hydro-meteorological intensity on FC variability by comparison of rainfall-induced high-flow events with baseline low-flow conditions. Fecal coliform concentration increased significantly in response to these events (Kistemann *et al.,* 2002; Signor *et al.,* 2005; Kay *et al.,* 2008). This response was amplified by the presence of urban and agricultural land within the watershed and was lowered for those that were more pristine.

The influence of annual precipitation variability on mean FC concentration of surface water was examined in order to assess the capacity of climate change to influence the total amount of surface source water fecal contamination. Above average seasonal and annual rainfall and river discharge was shown to generate corresponding trends in FC concentration for 58% of the 19 sites used in the study. During the El Niño event in 2002/03, precipitation decreased by 10-60% across BC, with negative deviations increasing with distance from the coast. This provided an opportunity to examine the influence of a province wide decrease in precipitation. Minimum annual FC concentrations were recorded with greatest frequency during this year, which suggests that FC transport was lower across the region as a result of lower precipitation. This observation was supported by associations between negative river discharge and FC deviations in spring and summer during the El Niño event relative to non-El Niño years.

Annual FC variability was related to hydro-meteorological variability with greater frequency in winter and spring than fall and summer. This is primarily attributable to the predominance of SD watersheds (15/19). Warmer temperatures in winter result in an increase rainfall which then drives a corresponding increase in mean FC concentrations. This is likely to occur in many BC watersheds where the proportion of winter precipitation in the form of rain increases with rising temperatures. Similarly, positive river discharge anomalies in spring, which indicate greater snowmelt resulting from higher winter snowpack accumulations, were associated with positive FC anomalies for SD watersheds. The upper ranges of temperature and rainfall anomalies observed in this study are in line with the projected climate norm towards the end of the century. It may be that years of correspondingly high fecal contamination may also be indicative of future mean levels.

Unexplained variability in the relationship between hydro-meteorological factors and FC concentration requires further investigation. Inter-annual FC concentration and hydro-meteorological relationships were observed in half of watersheds examined. This is a similar proportion to the number of watersheds in which seasonal FC concentration variability was significantly associated with hydro-meteorological variability. Factors determining the presence and strength of these relationships should be investigated in order to provide a basis for assessing watersheds at greater risk of surface water quality degradation. Variability in associations between FC concentration and hydro-meteorological factors among watersheds observed by Wilkes *et al.* (2009) was ascribed to differences in stream order, upstream land-use, and factors influencing contaminant transport and loading. Given the challenge of quantifying the influence of these factors on surface water fecal contamination, it is likely to be difficult to make predictions regarding the vulnerability of a specific source water location to hydro-meteorological impacts without robust baseline fecal indicator data for each season.

The use of secondary data may have introduced error that could not be controlled. This is especially so in regard to comparisons between sites. Data used were obtained from federal and provincial databases managed by Environment Canada and the BC Ministry of Environment. Fecal coliform data were selected and included on the basis of meeting the required bi-monthly sample frequency and the minimum number of years of sample duration for each study. Values were assumed to be comparable and sampling and enumeration methodologies consistent between samples and locations, which may not always have been the case. Given these assumptions, it still remains possible that different sampling frequencies and dates on which samples were obtained affected the capacity for climate and FC interactions to be identified. This reduces the validity of comparisons among sites. There was no indication of the error associated with each FC sample value, which was assumed to provide a representative indication of FC concentration on the day of sampling. This, however, is very challenging to achieve as many samples are usually required to provide a representative estimate of FC concentration (Meays *et al.,* 2006a).

The studies performed did not include specific information on watershed characteristics or provide the opportunity to control confounding factors known to influence the response of surface water fecal contamination to land-use and hydro-meteorological factors. The studies conducted were observational and did not involve any manipulation of the variables being examined and controlling for potentially confounding variables was not possible. This limits the extent to which causality can be ascribed to the associations observed between hydro-meteorological and land-use factors and FC variability, and the ability to provide specific reasons for the variability observed in these relationships.

The many factors within a watershed that influence the production, exposure, mobilization, and transport of fecal contaminants are discussed in detail in the introduction to this thesis. It is only possible to speculate as to which of these may have influenced the response, or absence thereof, of FC to land-use and hydro-meteorological factors. Explanatory factors within these watersheds that should be further investigated include: point sources of contamination (Tyrrel and Quinton, 2003); management practices, both good and bad (Davies and Mazumder, 2003); the area of impervious surfaces, including transportation corridors (Field and Sullivan, 2003); riparian vegetation (Tate *et al.,* 2004); deforestation in the watershed (Atwill *et al.,* 2002); soil structure (Ferguson *et al.,* 2003a); in situ growth and survival of FC (Meays *et al.,* 2005; Teifenthaler *et al.,* 2009); wildlife abundance and activity (Meays *et al.,* 2006b); recreational activity (McDonald *et al.,* 2008); and stream and sediment erosion (Dorner *et al.,* 2006), to name but a few. Quantifying or controlling these variables would present the opportunity to account for FC variability that could not be explained by the land-use and hydro-meteorological parameters utilized in this study. Furthermore, these factors can help provide an explanation for the variability in FC responses to climate and land-use impacts observed among and within watersheds.

The relationships between hydro-meteorological and FC variability presented in this thesis provide an explanation for the relationship between weather events and waterborne disease identified in previous studies. The majority of watersheds in Canada are SD, which were shown to experience peak surface water fecal contamination in spring and summer. This seasonality in source water fecal contamination is likely to account for the similar trend of seasonality in disease outbreak events in Canada shown in Figure 1.2.1 (Thomas *et al.,* 2006). Furthermore, the capacity for precipitation to increase FC concentration in surface water, indicated by inter-annual associations, provides mechanistic support for the relationship between heavy precipitation and waterborne disease outbreaks in North America (Curriero *et al.,* 2001).

These studies demonstrate the capacity for changes in land-use and climate to influence surface water fecal contamination, but also indicate the high variability of such interactions among watersheds. Changes to seasonal patterns of surface water fecal contamination within watersheds, due to shifts in the runoff regime, may also be accompanied by changes to the total amount of fecal contamination, in relation to changes in total precipitation. Greater agricultural and urban development in watersheds will tend to enhance the impact of these changes by increasing the amount of fecal contamination and it's transport through the watershed. Unexplained inconsistency and variability among these relationships at different sites, however, suggest that site-specific responses in fecal contamination to changes in the intensity of environmental forcing cannot be easily estimated from general relationships. Application of this work can be directed towards preparing for and mitigating changes in surface water fecal contamination anticipated within the watersheds examined. It should also provide an impetus and theoretical basis for investigating the potential impact of land-use and climate change on fecal contamination at other surface source water locations.

Bibliography

Allan, R. and Soden, B. 2008. Atmospheric warming and the amplification of precipitation extremes. Science 321, 1481-1484.

American Society for Microbiology (ASM). 1999. Microbial pollutants in our nation's water. American Society for Microbiology, Washington, D.C. 16 p.

Auld, H., Maclver, D., and Klaassen, J. 2004. Heavy rainfall and waterborne disease outbreaks: the Walkerton example. Journal of Toxicology and Environmental Health. (Part A) 67, 1879–1887.

Aramini, J., Stephen, C., Dubey, J., Engelstoft C., Schwantje H., and Ribble, C. 1999. Potential contamination of drinking water with Toxoplasma gondii oocysts. Epidemiological Infections 122, 305-315.

Aramini, J., McLean, M., Wilson, J., Holt, J., Copes, R., Allen, B. and Sears, W. 2000. Drinking water quality and health-care utilization for gastrointestinal illness in greater Vancouver. Canadian Communicable Disease Report 26(24), 211-214.

Arnone, R. and Walling, J. 2007. Waterborne pathogens in urban watersheds. Journal of Water and Health 05, 149-162.

Atwill, E., Hou, L., Karle, B., Harter, T., Tate, K., and Dahlgren, R. 2002. Transport of *Cryptosporidium parvum* oocysts through vegetated buffer strips and estimated filtration efficiency. Applied and Environmental Microbiology 68, 5517-5527

Avery, S., Moore, A., and Hutchinson, M. 2004. Fate of *Escherichia coli* originating from livestock faeces deposited directly onto pasture. Letters in Applied Microbiology 38, 355-359

Bartram, J. and Cairncross, S. 2010. Hygiene, Sanitation, and Water: Forgotten Foundations of Health. Public Library of Science Medicine 7(11)

Bates, B., Kundzewicz, Z., Wu, S., and Palutikof, J. Eds. 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva, 210 pp.

British Columbia Ministry of Environment (BC MoE, 2011a). Ecoregions. Obtained online on 13 June 2011 from http://www.env.gov.bc.ca/ecology/ecoregions

British Columbia Ministry of Environment (BC MoE, 2011b). Georgia Depression Ecoprovince. Obtained online on 13 June 2011 from www.env.gov.bc.ca/esd/distdata/ecosystems

Boxall, A., Hardy, A., Beulke, S., Boucard, T., Burgin, L., Falloon, P., Haygarth, P., Hutchinson, T., Kovats, R., Leonardi, G., Levy, L., Nichols, G., Parsons, S., Potts, L., Stone, D., Topp, E., Turley, D., Walsh, K., Wellington, E., and Williams, R. 2009. Impacts of climate change on indirect human exposure to pathogens and chemicals from agriculture. Environmental Health Perspectives 117:4 508-514

Cha, S., Lee, S., Park, Y., Cho K., Lee, S., and Kim, J. 2010. Spatial and temporal variability of fecal indicator bacteria in an urban stream under different meteorological regimes. Water Science and Technology 61.12 3102-3108

Charron, D., Thomas, K., Waltner-Toews, D., Aramini, J., Edge, T., Kent, R., Maarouf, A., and Wilson, J. 2004. Vulnerability of waterborne diseases to climate change in Canada: a review, Journal of Toxicology and Environmental Health (Part A) 67 1667–1677

Chevan, A., and Sutherland, M. 1991. Hierarchical partitioning. The American Statistician 45, 90-96

Chigbu, P., Gordon, S., and Strange, T. 2004. Influence of inter-annual variations in climatic factors on fecal coliform levels in Mississippi Sound. Water Research 38, 4341-4352

Christman, K. 1998. The History of Chlorine. Water World. Obtained online on 17th May 2010 from: www.waterandhealth.org/drinkingwater/history

Clark, H. 1907. Report of the committee on standard methods of water analysis American Public Health Association. 365-367

Cloete, T., Rose, J., Ford, T., and Nel, L. 2004. Microbial waterborne pathogens. IWA publishing Environment Canada. 2000. Groundwater—Nature's hidden treasure. Freshwater Series A-5. Available at www.ec.gc.ca/water/en/info/pubs/ FS/e_FSA5.htm.

Coffey, R., Cummins, E., Cormican, M., Flaherty, V.O., and Kelly, S. 2007. Microbial exposure assessment of waterborne pathogens. Human and Ecological Risk Assessment 13, 1313–1351.

Coffey, R., Cummins, E., Cormican, M., Flaherty, V.O., and Martin, C. 2010. Pathogen sources estimation and scenario analysis using the soil and water assessment tool (SWAT). Human Ecological Risk Assessment 16, 913–933.

Confalonieri, U., Menne, B., Akhtar, R., Ebi, K., Hauengue, M., Kovats, R., Revich B., and Woodward, A. 2007: Human health. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 391-431.

Curriero, F., Pat, J., Rose, J. and Subhash L. 2001. The Association Between Extreme Precipitation and Waterborne Disease Outbreaks in the United States, 1948–1994.

American Journal of Public Health 91(8), 1194-1199.

Davies, C., Ferguson, C., Kaucner, Krogh, M., Altavilla, N., Deere, D. and Ashbolt, N. 2003. Dispersion and transport of *Cryptosporidium* oocysts from fecal pats under simulated rainfall events. Applied and Environmental Microbiology 70, 1151-1159.

Davies, J. and Mazumder, A. 2003. Health and environmental policy issues in Canada: the role of watershed management in sustaining clean drinking water at surface sources. Journal of Environmental Management 68, 273-286

Delpla I., Jung, A., Baures, E., Clement, M., and Thomas, O. 2009. Impacts of climate change on surface water quality in relation to drinking water production. Environment International 35, 1225-1233

Demarchi, D. 1996. An Introduction to the Ecoregions of British Columbia, Wildlife Branch, Ministry of Environment, Lands and Parks, Victoria, British Columbia

Dorner, S., Anderson, W., Slawson, R., Kouwen, N., and Huck, P. 2006. Hydrologic modeling of pathogen fate and transport. Environmental Science Technology 40, 4746-4753.

Dorner, S., Anderson, W., Gaulin, T., Candon, H., Slawson, R., Payment P., and Huck, P. 2007. Pathogen and indicator variability in a heavily impacted Watershed. Journal of Water and Health 05(2), 241-257

Edge, T., Byrne, J., Johnson, R., Robertson, W., and Stevenson, R. 2008. Threats to sources of drinking water and aquatic ecosystem health in Canada. Environment Canada. Retrieved from: http://www.ec.gc.ca/inre-nwri/default.asp?lang=En&n=235D11EB-1&offset=2&toc=show

Eggertson, L. 2008. Investigative report: 1766 boil-water advisories now in place across Canada. Canadian Medical Association Journal 178 (10), 1261-1263.

Environment Canada. 2001. Threats to sources of drinking water and aquatic ecosystem health in Canada. National water resources research institute, Burlington, Ontario. NWRI scientific assessment report, series 1.

Environment Canada. 2010. Climate monitoring and data analysis (El Niño/La Niña). Retrieved from http://www.ec.gc.ca/adsc-cmda/Default.asp?lang=En&n=EBF3653A-1

Ferguson, C., Husman, A., Altavilla, N., Ashbolt, N., and Deere, D. 2003a. Fate and transport of surface water pathogens in watersheds. Critical Reviews in Environmental Science and Technology 33, 299-361

Ferguson, C., Altavilla, N., Ashbolt, N., and Deere, D. 2003b. Prioritizing watershed pathogen research American Waste Water Association 95(2) 92-102

Field, K. and Samadpour, M. 2007. Fecal source tracking, the indicator paradigm, and managing water quality. Water Research 41, 3517-3538

Field, R. and Sullivan, D. 2003. Wet-Weather Flow in the Urban Watershed. Lewis Publishers, Boca Raton, Florida

Fraser, J. 2002. Indicators for climate change in British Columbia, 2002. Ministry of water, land, and air protection.

Garcia-Armisen, T. and Servais, P. 2006. Respective contributions of point and non-point sources of *E. coli* and enterococci in a large urbanized watershed (the Seine River, France). Journal of Environmental Management 82, 512-518.

Greer, A., Ng, V., and Fisman, D. 2008. Climate change and infectious diseases in North America: the road ahead. Canadian Medical Association 178(6)

Gauthier, V., Barbeau, B., Tremblay, G., Millette, R., and Bernier, A. 2003. Impact of raw water turbidity fluctuations on drinking water quality in a distribution system. Journal of Environmental Engineering Science 2, 281-291.

Henson, S., Majowicz, S., Masakure, O., Sockett, P., MacDougall, L., Edge, V., Thomas, M., Fyfe, M., Kovacs, S., and Jones, A. 2008. Estimation of the costs of acute gastrointestinal illness in British Columbia, Canada International Journal of Food Microbiology 127, 43–52.

Hurley, T. 2012. Validation of a Canadian drinking source water quality index and its application to investigate the spatial scale of land use – source water quality relationships. Unpublished master's thesis, University of Victoria, Victoria, Canada.

IPCC. 2007. Climate Change 2007: Synthesis Report Summary for Policymakers

Kay, D., Crowther, J., Stapleton, C., Wyer, M., Fewtrell, L., Anthony, S., Bradford, M., Edwards, A., Francis, Hopkins, M., Kay, C., McDonald, A., Watkins, J., and Wilkinson, J. 2008. Faecal indicator organism concentrations and catchment export coefficients in the UK. Water Research 42, 2649-2661.

King, B., and Monis, 2007. Critical processes affecting *Cryptosporidium* oocyst survival in the environment. Parasitology 134, 309-323.

Kistemann, T., Claben, T., Koch, C., Dangendorf, F., Fischer, R., Gebel, J., Vacata, V., and Exner, M. 2002. Microbial load of drinking water reservoir tributaries during extreme rainfall and runoff. Applied and Environmental Microbiology. May p. 2199-2197

Kloot, R. 2006. Locating *E. coli* contamination in a South Carolina watershed. Journal of Environmental Management 83, 402-408.

Lemmen, D.S., Warren, F.J., Lacroix, J., and Bush, E., Eds. 2008. National Research Council (NRC). From Impacts to Adaptation: Canada in a Changing Climate 2007. Government of Canada, Ottawa, ON, 448 p.

Li, S., Sheng, G., Tan, X., and Zhang, Q. 2009. Water quality in the upper Han River basin, China: The impacts of land use/land cover in riparian buffer zone. Journal of Hazardous Materials 165, 317–324.

Lipp, E., Kurz, R., Vincent, R., Rodriguez-Palacios, C., Farrah, and S., Rose J. 2001a. The Effects of Seasonal Variability and Weather on Microbial Fecal Pollution and Enteric Pathogens in a Subtropical Estuary. Estuaries 24(2), 266-276.

Lipp, E., Schmidt, N., Luther, M., and Rose, J. 2001b. Determining the effects of El Niño-Southern Oscillation events on coastal water quality. Estuaries 24, No. 4, 491-497

Lorenzo, E., Cobb, K., Furtado, J., Schneider, N., Anderson, B., Bracco, A., Alexander, M., and Vimont, D. 2010. Central Pacific El Niño and decadal climate change in the North Pacific Ocean. Nature Geoscience 3, 762-765.

Lyautey, E., Lapen, D., Wilkes, G., McCleary, K., Pagotto, F., Tyler, K., Hartmann, A., Piveteau, P., Rieu, A., Robertson, W., Medeiros, D., Edge, T., Gannon, V., and Topp, E. 2007. Distribution and characteristics of *Listeria monocytogenes* isolates form surface waters of the South Nation River Watershed, Ontario, Canada. Applied and Environmental Microbiology 73, 5401-5410.

MacDougall, L., Majowicz, S., Dore, K., Flint, J., Thomas K., Kovacs, S., and Sockett, P. 2007. Under-reporting of infectious gastrointestinal illness in British Columbia, Canada: who is counted in provincial communicable disease statistics? Epidemiological Infections 136, 248–256.

MacKenzie WR, Hoxie NJ, Proctor ME, Gradus MS, Blair KA, Peterson DE, et al. 1994. A massive outbreak in Milwaukee of cryptosporidium infection transmitted through the public water supply. New England Journal of Medicine 331, 161–167.

McDonald, A., Chapman, P., and Fukasawa, K. 2008. Microbial status of natural waters in a protected wilderness area. Journal of Environmental Management 87, 600–608.

McMichael et al., World Health Organisation (WHO). 2004. Global climate change. Comparative quantification of health risks. Available at http://www.who.int/publications/cra/chapters 2, 1543-1650

Majowicz S., Edge, V., Fazil, A., McNab, W., Dore, K., Sockett, P., Flint, J., Middleton, D., McEwen, S., and Wilson, J. 2005. Estimating the under-reporting rate for infectious gastrointestinal illness in Ontario. Canadian Journal of Public Health 96, 178–181.

Manuta, N. and Hare, S. 2002. The Pacific Decadal Oscillation. Journal of Oceanography

58, 35-44.

Meays, C., Broersma, K., Nordin, R., and Mazumder, A. 2005. Survival of *Escherchia coli* in beef cattle fecal pats under different levels of solar exposure. Rangeland Ecology and Management 58, 279-283.

Meays, C., Broersma, K., Nordin, R., Mazumder, A., and Samadpour, M. 2006a. Diurnal variability in concentrations and sources of *E. coli* in three streams. Canadian Journal of Microbiology 52, 1130-1135.

Meays, C., Broersma, K., Nordin, R., Mazumder, A., and Samadpour, M. 2006b. Spatial and annual variability in concentrations and sources of E. coli in multiple watersheds. Environmental Science Technology 40, 5289-5296.

Murdock, T. and Spittlehouse, D. 2011. Selecting and Using Climate Change Scenarios for British Columbia. Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC, 39 pp.

National Research Council (NRC). 2001. Under the weather: Climate, ecosystems, and infectious disease. National Academy of Sciences.

National Research Council (NRC). 2004. Indicators for waterborne pathogens. Committee on indicators for waterborne pathogens. National Academy of Sciences.

O'Connor, D. 2002a. Part One Report of the Walkerton Commission of Inquiry, Chapter 2 – The impact on Walkerton. Retrieved from http://www.attorneygeneral.jus.gov.on.ca/english/about/pubs/walkerton/part1/

O'Connor, D. 2002b. Part Two Report of the Walkerton Commission of Inquiry, Chapter 4 – The physical causes of contamination. Retrieved from http://www.attorneygeneral.jus.gov.on.ca/english/about/pubs/walkerton/part2/

Parashar, U. Bresee, J. and Glass, R. 2003. The global burden of diarrheal disease in children. Bulletin of the World Health Organization 81, (4).

Parker, J., McIntyre, D., and Noble, R. 2010. Characterizing fecal contamination in stormwater runoff in coastal North Carolina. Water Research 44, 4186-4194

Parry, M., Canziani, O., Palutikof, J., Van der Linden, P., and Hanson, C. 2007. Contribution of working group 2 to the fourth assessment report of the Intergovernmental panel on climate change. Cambridge University Press, UK.

Patz, J., Campbell-Lendrum, D., Holloway, T., and Foley, J. 2005. Impact of regional climate change on human health. Nature 438, 310-317.

Patz, J., Olson, S., Uejio, C., and Gibbs, H. 2008a. Disease emergence from global climate change and land use. Medical Clinics of North America 92, 1473–1491

Patz, J., Vavrus, S., Uejio, C., and McLellan, S. 2008b. Climate change and waterborne disease risk in the Great Lakes region of the U.S. American Journal of Preventative Medicine 35(5), 451-458.

Perdek, J. Arnone, R., and Stinson, M. 2003. Managing Urban Watershed Pathogen Contamination. U.S. Environmental Protection Agency, Cincinnati, Ohio EPA/600/R-03/111

Ritter, L., Solomon, K., Sibley, P., Hall, H., Keen, P., Mattu, G., and Linton, B. 2002. Sources, pathways, and relative risks of contaminants in surface water and groundwater: a perspective prepared for the Walkerton enquiry. Journal of Toxicology and Environmental Health (Part A) 65, 1–142.

Rose, J. 1997. Environmental ecology of *cryptosporidium* and public health implications. Annual Review of Public Health 18, 135–161

Sargeant, J., Majowicz, S., and Snelgrove, J. 2008. The burden of acute gastrointestinal illness in Ontario, Canada, 2005-2006. Epidemiological Infections 136, 451–460.

Schaffter, N., and Parriaux, A. 2002. Pathogenic-bacterial water contamination in mountainous catchments. Water Research 36, 131-139.

Schaffter, N., Zumstein, J., and Parriaux, A. 2004. Factors Influencing the Bacteriological Quality in Mountainous Surface and Groundwaters. Acta hydrochimica hydrobiological 32(3), 225

Schnorbus, M., Bennett, K., Werner, A., and Berland, A. 2011. Hydrologic impacts of climate change in the Peace, Campbell, and Columbia watersheds, British Columbia, Canada. Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC, 157pp.

Schuster C., Ellis A., Robertson, W., Charron, D., Aramini, J., Marshall, B., and Medeiros, D. 2005. Infectious disease outbreaks related to drinking water in Canada, 1974–2001. Canadian Journal of Public Health 96(4), 254–258.

Shabbar, A., Bonsal, B., and Khandekar, M. 1997. Canadian precipitation patterns associated with the Southern Oscillation. Journal of Climate 10, 3016-3027.

Shrestha, R., Berland, A., Schnorbus, M., and Werner, A. 2011. Climate Change Impacts on Hydro-Climatic Regimes in the Peace and Columbia Watersheds, British Columbia, Canada. Pacific Climate Impacts Consortium, University of Victoria, Victoria, BC, 37 pp.

Signor, R., Roser, D., Ashbolt, N., and Ball, J. 2005. Quantifying the impact of runoff events on microbiological contaminant concentrations entering surface drinking source waters. Journal of Water and Health 03.4 453-468

Sigua, G., Palhares, J., Kich, J., Mulinari, M., Mattei, R., Klein, J., Muller, S., and

Plieske, G. 2010. Microbiological Quality Assessment of Watershed Associated with Animal-Based Agriculture in Santa Catarina, Brazil. Water Air Soil Pollution 210, 307–316.

Smith, R., Scherer, R., and Dobson, D. 2008. Snow cover extent during spring snowmelt in the south-central interior of British Columbia. BC Journal of Ecosystems and Management 9(1), 57-70.

Stirling, R., Aramini, J., Ellis, A., Lim, G., Meyers, R., Fleury, M., and Werker, D. 2001. Waterborne cryptosporidiosis outbreak North Battleford, Saskatchewan, spring 2001 Canadian Communicable Disease Report 27, 185–192.

Tate, K., Pereira, M., and Atwill, E. 2004. Efficacy of vegetated buffer strips for retaining *Cryptosporidium parvum*. Journal of Environmental Quality 33, 2243–225

Thomas, K., Majowicz, S., MacDougall, L., Sockett, P., Kovacs, S., Fyfe, M., Edge, V., Dore, K., Flint, J., Henson, S., and Jones, A. 2006. Population distribution and burden of acute gastrointestinal illness in British Columbia, Canada. BMC Public Health 6, 307–317.

Thomas, K., Charron, D., Waltner-Toews, D., Schuster, C., Maarouf, A., and Holt, J. 2006. A role of high impact weather events in waterborne disease outbreaks in Canada, 1975 - 2001, International Journal of Environmental Health Research 16(3) 167-180

Tiefenthaler, L., Stein, E., and Lyon, G. 2009. Fecal indicator bacteria (FIB) levels during dry weather from Southern California reference streams. Environmental Monitoring Assessment 155, 477-492.

Tyrrel, S. and Quinton, J. 2003. Overland flow transport of pathogens from agricultural land receiving fecal wastes. Journal of Applied Microbiology 94, 87–93.

Traister, E. and Anisfeld, S. 2006. Variability of indicator bacteria at different time scales in the upper Hoosic River watershed. Environmental Science Technology 40, 4990-4995.

Unger, S. 2008. Microbial Source Tracking: New forensic approaches to identify sources of fecal pollution, *Environment Canada*. Available at: http://www.ec.gc.ca/scitech/default.asp?lang=en&n=4B40916E1&xsl=privateArticles2,viewfull&po=B2DDBB17

USEPA, 2002. NPDES - Stormwater Program, www.epa.gov/npdes/stormwater. Feasibility of a New Approach (The Annapolis Protocol),

Walters, S., Thebo, A., and Boehm, A. 2010. Impact of urbanization and agriculture on the occurrence of bacterial pathogens and stx genes in coastal waterbodies of central California. Water Research 45, 1752-1762.

Waltner-Toews, D. 2005. Links between climate, water and waterborne illness, and projected impacts of climate change. Health policy research program, summary of research results.

Warrington P. 2001a. Water quality criteria for microbiological indicators. British Columbia Ministry of Environment. Retrieved 6th September 2011 from: http://www.env.gov.bc.ca/wat/wq/BCguidelines/microbiology/microbiology.html

Warrington P. 2001b. Aquatic pathogens, introduction. British Columbia Ministry of Environment. Retrieved 6th September 2011 from: http://www.env.gov.bc.ca/wat/wq/reference/introduction.html#tofc

WDFW (Washington department of fish and wildlife). 2011. Summary of climate change effects on major habitat types in Washington State. Retrieved 10th December 2011 from: http://wdfw.wa.gov/publications/01201/wdfw01201.pdf

Wentz, F., Ricciardulli, L., Hilburn, K., and Mears, C. 2007. How much rain will global warming bring? Science 317, 233-235.

WHO (World Health Organisation). 2001. Endemic and epidemic infectious intestinal disease and its relationship to drinking water. In: Fewtrell L and Bartram J (eds), Water quality– Guidelines, standards and health: Assessment of risk and risk management for water-related infectious disease, pp 61–88. IWA Publishing, London, UK

WHO (World Health Organisation) McMichael et al. 2004. Global climate change. Comparative quantification of health risks. Available at http://www.who.int/publications/cra/chapters/volume2/1543-1650.pdf

Wilkes, G., Edge, T., Gannon, V., Jokinen, C., Lyautey, E., Medeiros, D., Neumann, N., Ruecker, N., Topp, E., and Lapen, D. 2009. Seasonal relationships among indicator bacteria, pathogenic bacteria, *Cryptosporidium* oocysts, *Giardia* cysts, and hydrological indices for surface waters within an agricultural landscape. Water Research 43, 2209-2223.

Woodall, C. 2009. Waterborne diseases – What are the primary killers? Desalination 248, 616–621.

Zhang, X., Vincent, L., Hogg, W., and Niitsoo, A. 2000. Temperature and precipitation trends in Canada during the 20th century. Atmosphere–Ocean 38, 395– 429.

Zhang, X., Hogg, W., and Mekis, E. 2001. Spatial and temporal characteristics of heavy precipitation events over Canada. Journal of Climate 14, 1923-1936.

Zhu, Z., Broersma, K., and Mazumder, A. 2011. Model assessment of cattle and climate impacts on stream fecal coliform pollution in the Salmon River watershed, British Columbia, Canada. Water Air and Soil Pollution 215, 155-176

Appendix A Land-use data

Table A.1. Land type within sample watersheds (%)

Site name	Site no.	Area (m2)	Agriculture	Alpine	Barren	Fresh water	Glacier	Mining	Old forest	Range	Burned	Logged	Recreation	Res agri	Selec log	Sub alpine	Urban	Wetland	Young forest	Impacted	elevation
Callaghan Creek	1	74942482	0	35.03	0	2.4371	11.575	0	42	0	0	0	0	0	0	9.006	0	0	0	0	1615.42
Callaghan Creek at Hway 99	2	53883624	0	6.476	0	0	0.9949	0	58.8	0	0	29.09	0	0	2.06	0	0	0.3231	2.286	0	1126.75
Cheakamus River below sewage plant	3	19231693	0	1.81	0	0	0	0	44.7	0	0	48.6	0	0	0	0	1.839	0	3.01	1.83889	896.8
Cheakamus River on lake road	4	45527390	0	5.381	2.6413	2.0779	0	0	63.2	0	0	15.02	0	0	0	5.744	0	1.479	4.431	0	1113.75
Chilcotin River near Christie	5	140544937	5.668988	0	0	1.499	0	0	32.9	13.92	0	8.396	0	0	3.88	0	0.431	3.4676	29.84	20.0199	875.221
Coldstream creek at Kirkland	6	121509986	18.44905	0	0	0	0	0.146	6.25	12.47	0	7.238	0.0081376	0	3.85	0	2.373	0	49.21	33.3032	1039.84
Columbia River at Birchbank	7	171724980	0.729047	0	4.8482	5.2839	0	0.101	5.52	0.182	0	4.705	0	0.03	3.06	0	16.2	0	59.35	17.136	893.032
Columbia River at Nicholson	8	125439951	0.256115	2.782	1.871	3.1157	0	0.93	2.4	0	0	5.805	1.2202085	2.32	1.27	2.214	7.6	9.4759	58.74	11.3994	1103.02
Columbia River at Waneta	9	135007450	0.808045	0	4.8714	2.2048	0	0	0.34	11	0	8.5	0.571704	8.27	2.69	0	12.78	0	47.97	33.4281	855.073
Cowichan River	10	69436609	0.487934	0	0	0.4332	0	0	5.55	0	0	12.29	0	4.51	2.21	0	17.07	2.9792	54.47	22.0654	192.103
Elk river at Hway 93	11	105100486	1.170114	4.281	11.9	0	0	0	6.11	15.63	0	2.647	0	0	2.34	4.349	1.953	3.2602	46.35	18.755	1257.16
Elk River at Sparwood	12	193732299	5.713928	2.98	2.7468	0	0	10.94	1.4	0	0	8.462	0.1795906	0.77	6.35	3.704	3.694	2.8098	50.25	10.3623	1470.68
Englishman River	13	47358160	0	0	0	0	0	0.811	5.21	0	0	13.81	0	0	0	0	7.271	0.9381	71.96	7.27141	195.471
Fraser River at Hansard	14	217958300	2.537679	0	0	5.3683	0	0	51.7	0	0	11.51	0	0	3.06	0	0.145	7.4719	18.2	2.68269	671.83
Fraser River at Hope	15	173549192	0	3	0	3.6837	0	0.108	26.6	0	0	7.705	0	0	0	3.276	1.077	0.1086	54.48	1.07696	844.444
Fraser River at Marguerite	16	230898587	4.954608	0	0	3.632	0	0	11.8	0.236	0	16.4	0	0	5.65	0	0.072	5.0324	52.23	5.26234	783.953
Fraser River at Red pass	17	223700734	0	25.16	0.6757	6.3372	1.6835	0.226	29.1	0	0	0	0	0	0	8.954	0	2.3043	25.51	0	1700.82
Kettle River at Carson	18	109941266	11.00585	0	6.673	0	0	0.248	3.02	14.1	0	0.854	0	0	1.9	0	6.665	0.6196	54.92	31.768	826.815
Kettle River at Midway	19	66483404	23.64736	0	0.3805	0	0	0	0.26	45.33	0	1.155	0	0	3.17	0	0.126	0.6541	25.27	69.1066	788.647
Koksilah River at Highway 1	20	78247984	22.83629	0	0	0	0	0	0	0	0	7.382	0	13.8	2.27	0	2.057	0	51.64	38.7122	196.92
Kootenay River at Creston	21	151824163	19.21218	1.121	7.5738	2.4712	0	0	0.83	0.386	0	2.641	0	2.1	0	0	1.55	14.027	48.09	23.2473	1132.61
Kootenay River at Fenwick	22	159641199	10.22406	0	1.378	2.9312	0	0.07	7.66	7.22	0	7.53	0	0	8.53	0	0.592	9.7292	44.13	18.0352	873.65
Leech River	23	43173338	0	0	0.0684	0.6069	0	0	14.8	0	0	69.29	0	0	0	0	0	0.7842	14.47	0	421.231
Mission creek at lakeshore rd. bridge	24	169481820	16.11774	0	0.3975	0	0	0	7.61	6.296	0	9.78	0.8427913	2.15	6.77	0	5.611	0.2117	44.21	31.0153	991.884
Moyie River	25	177358593	1.868965	2.321	3.4439	0	0	0	3.83	0	0	9.316	0	0	11.1	0	0.354	0.5393	67.19	2.22338	1334.91
Myers Creek	26	55452883	6.330499	0	1.5695	0.2851	0	0	2.59	30.11	0	0	0	0	24	0	0	0	35.15	36.4436	868.316
Nechako River	27	258001129	10.57034	0	0	2.5066	0	0.941	8.53	0	0	6.871	0	0	9.14	0	7.062	1.1041	53.27	17.6336	661.737
Nicola River	28	138642553	0.543636	0	0	0.1115	0	0	38.1	20.86	0	1.046	0	0	9.31	0	0	0.2156	29.76	21.4051	1073.35
North Alouette	29	81901722	0	0	0.4667	12.3	0	0	7.31	0	0	3.09	0	0	0	1.021	12.76	0	63.06	12.7591	644
Okanagan River at Oliver	30	138453531	22.1002	0	0	2.4887	0	0	9.61	47.33	0	0.585	0	0	0.52	0	4.24	0	13.13	73.6735	540.711
Peace River	31	11295007	44.81919	0	2.9012	7.7599	0	0	0	0	0	2.282	0	0	0	0	0	0	42.24	44.8192	526.333
Pend D'Orielle at Waneta	32	149469144	3.819411	0.195	1.2031	3.1207	0	0	9.34	9.765	0	13.82	0	0	19.9	0	0.609	0	38.26	14.1931	1030.56
Pend D’Orielle at US boarder	33	38852840	0	0	5.2597	1.0558	0	0	0.43	8.227	0	8.464	0	0	16.1	0	0	0.4772	59.96	8.22733	998.952
Qunisam River near the mouth	34	92364254	0	0	0.9859	2.1619	0	0	3.82	0	0	7.857	0	0	0	0	0.972	2.0998	82.11	0.97182	169.68
Salmon River at Falkland	35	215297781	17.24027	0	1.4501	0.7309	0	0	15.7	4.626	0	2.275	0	0	2.56	0	0.009	0	55.43	21.8756	1025.83
Salmon river at Salmon Arm	36	147354543	14.98454	0	0.4222	0	0	0	16.1	0	10.334	10.42	0.4932457	0	4.78	0	0.796	0.195	41.43	16.2737	1128.82
Salmon River at Silver Creek	37	147191284	13.99972	0	0.2049	0.5124	0	0	4.78	1.234	0	8.852	0	0	9.39	0	0	0	61.02	15.2337	1078.06
San Juan River	38	87560026	0	0	0	0	0	0	24	0	0	26.03	0	0	0	0	0	1.3113	48.69	0	436.353
Similkameen River at Princeton	39	106816800	2.631878	0	0	0	0	0.847	27.3	5.683	0	1.199	0	0	3.76	0	1.823	0.7619	56.02	10.1377	925.978
Similkameen River at US boarder	40	191405348	17.28197	0.498	1.6644	2.3705	0	0	29	22.2	0	1.347	0	2.08	0	0	0.985	2.2286	20.36	42.546	960.52
Sooke Lake	41	80123241	0	0	0	7.13	0	0	44.9	0	0	30.53	0	0	0	0	0	0.3341	17.06	0	374.966
Sumas River at US border	42	35312435	52.6237	0	0	2.2357	0	0	3.29	0	0	4.792	0	0	0	0	1.675	1.3025	34.08	54.2987	231.667
Thompson River	43	154229226	3.34553	0	0.7055	1.6	0	0	48.2	26.07	0	0.501	0	0	9.12	0	0.265	0	10.19	29.6801	838.857

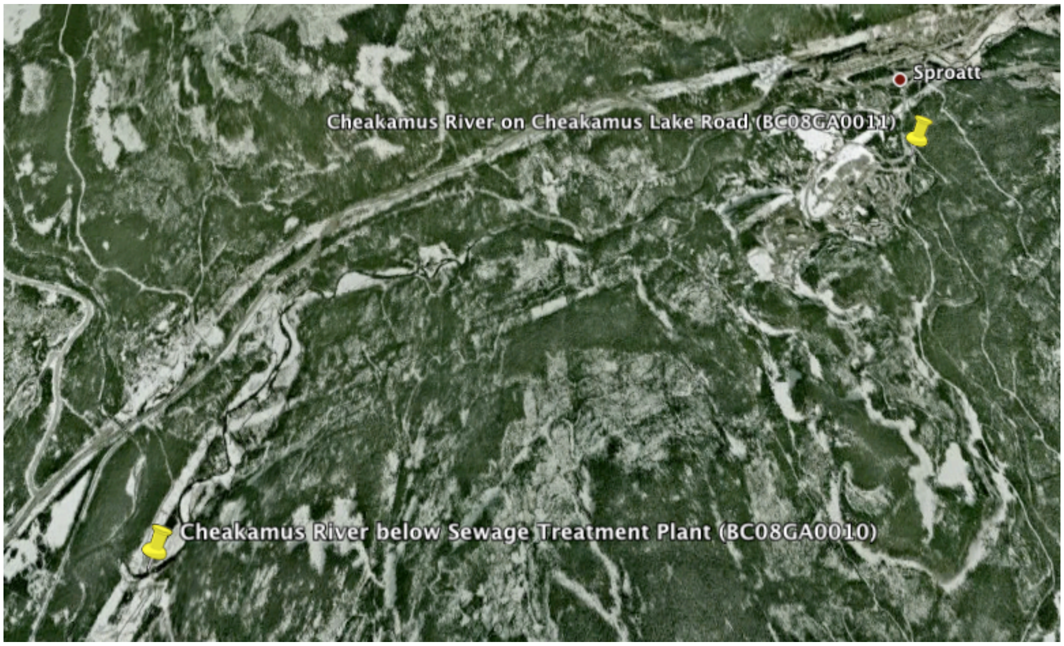

Figure A.1. The respective locations of site 4, upstream of the sewage treatment plant on the Cheakamus River, and site 3, downstream of the sewage treatment plant on the Cheakamus River

Figure A.2. Site 4 on the Cheakamus River and the sewage treatment plant located downstream

GIS information

Freshwater Atlas Assessment Watersheds

https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=4212&amp%3BrecordSet=ISO19115

The Freshwater Atlas contains fully connected stream network and derived watershed boundaries for the entire province. The current version of the Freshwater Atlas is based on the TRIM data completed in 1996.
Data last revised on: 2008-09-01

Baseline Thematic Mapping Present Land Use Version 1 Spatial Layer

https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=43171&recordSet=ISO19115

This layer represents Land use polygons as determined by a combination of analytic techniques, mostly using Landsat 5 image mosaics. BTM 1 was done on a federal satellite image base that was only accurate to about 250m. The images were geo-corrected, not ortho-corrected, so there is distortion in areas of high relief.

Data managed by Malcolm Gray at the Crown Registries and Geographic Base Branch (ILMB)

Appendix B Seasonal fecal coliform and hydro-meteorological data

Table B.1. Mean seasonal fecal coliform data (CFU 100ml^{-1})

Site name	Site no.	Annual	Spring	Summer	Fall	Winter
Callaghan Creek	1	1.13087532	1.166529	1.065041	1.165914	1
Callaghan Creek at Hway 99	2	1.35768671	1.56149	1.173964	1.42673	1.357271
Cheakamus River below sewage plant	3	4.53506293	7.253177	1.25802	1.73958	31.99152
Cheakamus River on lake road	4	1.14545776	1	1.054766	1.071773	1.251033
Chilcotin River near Christie	5	2.32708047	3.735914	1.919127	1.591433	1.105032
Coldstream creek at Kirkland	6	288.81052	195.4563	395.8561	151.1504	174.4589
Columbia River at Birchbank	7	1.58498996	1.444893	2.207398	1.497353	1.28053
Columbia River at Nicholson	8	2.01157184	2.022802	4.527532	1.134313	1
Columbia River at Waneta	9	4.83508054	2.961798	8.443102	7.472537	2.681692
Cowichan River	10	9.90578814	3.280415	13.90117	24.7456	6.121021
Elk river at Hway 93	11	3.18408158	2.823628	5.316029	2.070897	3.240101
Elk River at Sparwood	12	1.87284137	1.810739	3.210706	1.685991	1
Englishman River	13	18.650509	7.227953	35.96157	25.33387	13.02831
Fraser River at Hansard	14	4.05320173	3.091658	5.772551	3.891998	1.782602
Fraser River at Hope	15	16.3655916	15.02729	14.4807	18.44414	18.21399
Fraser River at Marguerite	16	39.4788554	36.79344	41.00262	41.75485	37.45098
Fraser River at Red pass	17	1.14204489	1.090508	1.09798	1.265386	1.110735
Kettle River at Carson	18	4.81055559	5.121274	11.77407	5.559819	1.512787
Kettle River at Midway	19	7.8403952	8.714832	16.93156	8.730408	2.45829
Koksilah River at Highway 1	20	19.3339599	10.11215	47.75864	31.65852	7.49243
Kootenay River at Creston	21	3.12325757	2.940595	7.82835	2.584175	1.593106
Kootenay River at Fenwick	22	3.18258181	2.800952	7.665043	2.696096	1.3135
Leech River	23	<1	<1	<1	<1	<1
Mission creek at lakeshore rd. bridge	24	55.7140075	14.60443	70.10383	43.21878	189.56
Moyie River	25	4.25136458	2.670685	7.436986	3.531724	5.830952
Myers Creek	26	26.2819431	22.56449	73.27502	31.70582	7.518664
Nechako River	27	4.64524986	7.648047	3.618876	2.454827	7.296171
Nicola River	28	9.55375625	12.04693	13.80111	10.20059	2.256426
North Alouette	29	9.16579941	3.05723	24.25464	14.33106	3.090699
Okanagan River at Oliver	30	6.39834023	5.023419	17.09189	4.803139	3.485599
Peace River	31	3.54936178	2.613482	9.726933	2.252703	2.086909
Pend D'Orielle at Waneta	32	1.21630942	1.112531	1.299047	1	1.613781
Pend D’Orielle at US boarder	33	1.09359982	1.15711	1.037155	1.109088	1.071773
Qunisam River near the mouth	34	15.3147456	4.297575	27.29472	25.49051	7.019849
Salmon River at Falkland	35	66.182548	52.91065	137.2469	68.42668	21.96139
Salmon river at Salmon Arm	36	71.3703653	58.98552	92.27549	77.53205	38.72548
Salmon River at Silver Creek	37	72.126775	87.49178	104.0079	63.1036	14.99852
San Juan River	38	5.53505955	2.722771	6.830233	23.53572	3.000627
Similkameen River at Princeton	39	2.22744326	2.134683	3.635862	2.158456	1.373141
Similkameen River at US boarder	40	4.25688586	6.566339	5.972513	4.36667	1.448289
Sooke Lake	41	<1	1.011619	1.216783	<1	1.087648
Sumas River at US border	42	305.375128	274.036	236.6614	301.6185	483.6739
Thompson River	43	2.58644737	2.841648	2.081225	3.259701	2.35738

Table B.2. Mean seasonal rainfall data (mm)

Site name	Site no.	Annual	Spring	Summer	Fall	Winter
Callaghan Creek	1	3.040909	1.377778	0.6363636	3	7.711111
Callaghan Creek at Hway 99	2	2.591429	1.553333	0.8956522	3.166667	5.75
Cheakamus River below sewage plant	3	2.432	1.363158	0.8636364	2.85	5.75
Cheakamus River on lake road	4	3.057143	2.7	0	3.42	8.0625
Chilcotin River near Christie	5	0.4166667	0.2166667	0.5583333	0.823077	0
Coldstream creek at Kirkland	6	0.771875	1.229167	0.9666667	0.2875	0.08888889
Columbia River at Birchbank	7	1.318817	0.8291667	1.157143	1.495652	1.860465
Columbia River at Nicholson	8	0.7282051	0.6909091	1.5	0.2545455	0
Columbia River at Waneta	9	1.215868	1.04382	1.151136	1.257647	1.458333
Cowichan River	10	2.971357	2.010417	1.917391	4.222222	3.347619
Elk river at Hway 93	11	0.6912698	0.5375	1.343243	0.4666667	0.1619048
Elk River at Sparwood	12	1.190805	0.3913043	2.595652	0.8481481	0.8571429
Englishman River	13	4.3125	3.645455	2.082353	3.485714	8.371429
Fraser River at Hansard	14	1.835294	1.775	2.585714	1.516667	0.12
Fraser River at Hope	15	13.56707	12.77692	6.1	21.8375	14.68205
Fraser River at Marguerite	16	2.597581	2.415152	3.151282	3.481818	0.2421053
Fraser River at Red pass	17	2.040136	1.0525	5.202941	1.6975	0.3939394
Kettle River at Carson	18	3.47963	4.409524	3.943902	3.935	1.523077
Kettle River at Midway	19	2.704651	4.06383	2.637209	2	1.913514
Koksilah River at Highway 1	20	2.931156	2.053191	1.726087	4.267742	3.245455
Kootenay River at Creston	21	4.093865	3.665116	4.579487	5.043182	2.951351
Kootenay River at Fenwick	22	2.338806	2.35	2.478947	3	1.153846
Leech River	23	NA	NA	NA	NA	NA
Mission creek at lakeshore rd. bridge	24	0.8428571	1.16	0.8666667	1.085714	0
Moyie River	25	3.909375	5.111111	2.82	4.372727	1.4
Myers Creek	26	2.249167	1.902857	2.63125	1.522222	3
Nechako River	27	3.67	2.913953	6.220455	4.468182	0.725641
Nicola River	28	1.774138	2.005882	2.222222	1.493333	0.8
North Alouette	29	18.07297	11.24	8.809091	20.24348	36.38571
Okanagan River at Oliver	30	1.840936	2.569048	1.457447	1.686047	1.689744
Peace River	31	2.518519	0.8285714	6.741026	1.410345	0.056
Pend D'Orielle at Waneta	32	3.856818	3.846154	3.6	4.59	3.375
Pend D’Orielle at US boarder	33	2.615854	1.973684	1.821053	4.458333	1.77
Qunisam River near the mouth	34	10.83571	3.5	2.5	12.3	25.48889
Salmon River at Falkland	35	1.101858	1.112097	1.233696	1.203846	0.6696078
Salmon river at Salmon Arm	36	1.102659	1.430482	1.426822	1.270219	0.2678288
Salmon River at Silver Creek	37	1.258333	0.5526316	1.155556	2.344444	0.4
San Juan River	38	29.81667	27.725	10.11429	48.10769	34.02353
Similkameen River at Princeton	39	1.703226	1.307843	1.623404	2.875	0.895
Similkameen River at US boarder	40	1.905063	1.832609	1.87	1.865	2.103125
Sooke Lake	41	2.776527	1.011619	0.8268657	2.776527	6.299663
Sumas River at US border	42	21.86182	20.54444	8.9	24.38235	37.64167
Thompson River	43	1.625325	1.954762	2.516667	1.341667	0.4176471

Table B.3. Mean seasonal river discharge data (m^3 sec)

Site name	Site no.	Annual	Spring	Summer	Fall	Winter
Callaghan Creek	1	21.07864	13.79889	37.49091	21.33333	7.874444
Callaghan Creek at Hway 99	2	22.13214	14.23533	35.37826	19.55611	12.14357
Cheakamus River below sewage plant	3	22.43667	16.18053	36.24545	20.3955	12.14357
Cheakamus River on lake road	4	24.52238	17.55455	34.85385	25.977	15.49625
Chilcotin River near Christie	5	99.61875	62.09167	218.5	75.56154	39.3
Coldstream creek at Kirkland	6	0.2542187	0.489125	0.2548667	0.0240625	0.03588889
Columbia River at Birchbank	7	1878.559	1493.667	2489.184	1751.152	1748.674
Columbia River at Nicholson	8	1.18641	0.9772727	2.092833	0.6915455	0.5598
Columbia River at Waneta	9	2580.898	2406.292	3344.773	2244.706	2260
Cowichan River	10	49.96106	47.00833	8.043043	42.41857	110.5595
Elk river at Hway 93	11	23.34071	21.59531	43.53784	14.1925	6.097619
Elk River at Sparwood	12	42.88046	45.75652	70.1087	29.37778	19.46429
Englishman River	13	12.10577	15.56545	2.445294	6.150214	27.07357
Fraser River at Hansard	14	574.1165	467.9312	954.9643	389.5833	109.8
Fraser River at Hope	15	4.64739	4.355051	6.19	4.360475	3.414513
Fraser River at Marguerite	16	1465.226	1456.424	2324.795	1022.242	485.5263
Fraser River at Red pass	17	40.36238	19.71725	110.8294	28.2925	7.414545
Kettle River at Carson	18	79.33605	174.4402	105.0493	13.48725	17.42154
Kettle River at Midway	19	43.36064	97.42851	52.45233	7.744444	7.430811
Koksilah River at Highway 1	20	9.157332	7.265702	0.5340435	8.33621	21.35023
Kootenay River at Creston	21	146.0699	122.6581	346.6769	81.21136	38.95676
Kootenay River at Fenwick	22	159.6112	159.1406	307.9789	91.22105	43.3
Leech River	23	NA	NA	NA	NA	NA
Mission creek at lakeshore rd. bridge	24	12.04167	20.18667	15.582	1.231714	0.918
Moyie River	25	16.58594	35.09778	15.212	4.388182	7.24
Myers Creek	26	42.56075	89.50343	51.94531	6.231481	5.545
Nechako River	27	234.3106	186.6465	437.75	170.9659	128.8077
Nicola River	28	26.82879	51.44882	24.475	8.312667	14.525
North Alouette	29	2.481635	1.414467	0.8966818	2.763087	5.653286
Okanagan River at Oliver	30	14.46234	17.10119	19.29617	10.63674	10.01308
Peace River	31	1463.185	1469.762	1478.385	1316.655	1598.4
Pend D'Orielle at Waneta	32	2514.545	2276.154	3283.846	2317	1898.75
Pend D’Orielle at US boarder	33	2388.78	2187.368	2926.316	2260	2224
Qunisam River near the mouth	34	8.489286	9.65	2.955385	8.891429	15.08333
Salmon River at Falkland	35	3.152703	8.248823	3.103114	0.9376923	0.999147
Salmon river at Salmon Arm	36	4.441938	9.583387	4.758422	1.437266	1.917209
Salmon River at Silver Creek	37	6.157333	14.19579	3.710778	1.319778	1.834
San Juan River	38	46.38572	36.74437	5.694929	61.87415	77.12588
Similkameen River at Princeton	39	19.62995	33.75706	25.03383	9.87375	6.97575
Similkameen River at US boarder	40	40.63449	77.10804	36.75775	22.6585	15.51969
Sooke Lake	41	1.471252	1.710617	0.1134925	1.471252	5.271424
Sumas River at US border	42	4.672309	3.871111	1.053882	3.915941	11.47083
Thompson River	43	729.8766	640.4524	1426.786	440.9722	285.3529

Table B.4. Mean seasonal Temperature data (^{0}C)

Site name	Site no.	Annual	Spring	Summer	Fall	Winter
Callaghan Creek	1	8.55	6.188889	17.3	9.733333	-1.755556
Callaghan Creek at Hway 99	2	8.782857	7.166667	16.13478	8.427778	-1.107143
Cheakamus River below sewage plant	3	9.084	8.189474	16.50909	8.9	-1.107143
Cheakamus River on lake road	4	9.916667	8.827273	16.87692	10.09	-0.1125
Chilcotin River near Christie	5	4.820833	4.808333	13.70833	4.576923	-4.572727
Coldstream creek at Kirkland	6	10.14375	11.4	20.04667	5.71875	-1.844444
Columbia River at Birchbank	7	9.555914	9.622917	19.46735	8.404348	-0.5813953
Columbia River at Nicholson	8	8.253846	9.090909	17.81667	3.409091	-5.88
Columbia River at Waneta	9	9.47994	9.249438	19.23295	8.295294	-0.7569444
Cowichan River	10	10.36734	9.50625	18.03043	10.01111	3.492857
Elk river at Hway 93	11	7.884127	7.665625	17.66216	5.963889	-5.719048
Elk River at Sparwood	12	6.136782	4.586957	14.75652	3.892593	-1.15
Englishman River	13	10.025	9.381818	17.44118	7.5	4.05
Fraser River at Hansard	14	7.588235	5.36875	15.16786	3.988889	-1.84
Fraser River at Hope	15	11.3122	10.24615	17.88261	11.8275	4.1
Fraser River at Marguerite	16	6.523387	5.133333	14.71538	4.427273	-4.236842
Fraser River at Red pass	17	3.971429	3.3575	13.95	3.805	-5.363636
Kettle River at Carson	18	8.639506	8.616667	18.46829	9.3175	-2.364103
Kettle River at Midway	19	8.416279	8.67234	18.33953	7.871111	-2.778378
Koksilah River at Highway 1	20	10.35025	9.538298	18.0913	10.04355	3.556818
Kootenay River at Creston	21	8.904294	7.972093	18.90256	8.615909	-0.2081081
Kootenay River at Fenwick	22	7.884328	7.271875	17.46842	6.889474	-3.915385
Leech River	23	NA	NA	NA	NA	NA
Mission creek at lakeshore rd. bridge	24	11.33333	13.6	20.46667	4.457143	-0.6
Moyie River	25	12.875	11.34444	20.54	9.318182	1
Myers Creek	26	11.37	11.06	21.4375	10.32222	0.4846154
Nechako River	27	5.074706	4.87907	14.81364	4.527273	-5.079487
Nicola River	28	12.51552	13.06471	20.58889	8.253333	1.175
North Alouette	29	10.68108	8.753333	16.89091	10.02174	4.071429
Okanagan River at Oliver	30	11.16842	11.10238	21.18298	10.8814	-0.5128205
Peace River	31	3.539259	1.797619	14.47949	4.362069	-11.556
Pend D'Orielle at Waneta	32	10.68409	8.73077	19.87692	9.69	0.1625
Pend D’Orielle at US boarder	33	9.77317	9.847368	21.48947	9.158333	-0.69
Qunisam River near the mouth	34	10.12619	8.3	17.74615	8.6	2.711111
Salmon River at Falkland	35	10.76081	10.69677	19.86793	8.162637	-0.9539216
Salmon river at Salmon Arm	36	7.946304	7.913841	18.54279	7.487931	-2.388748
Salmon River at Silver Creek	37	10.67167	10.40526	18.11667	7.538889	-3.84
San Juan River	38	9.521667	9.45	15.59286	9.184615	4.847059
Similkameen River at Princeton	39	7.414516	7.319608	17.32766	7.214583	-3.8725
Similkameen River at US boarder	40	11.93354	11.79783	21.3625	10.99	1.521875
Sooke Lake	41	11.62838	10.33333	17.69104	11.62838	4.387879
Sumas River at US border	42	12.7	11.75556	18.88235	11.41765	6.466667
Thompson River	43	10.03701	9.37381	20.39524	8.280556	-0.0794118

Appendix C Annual fecal coliform and hydro-meteorological data

Table C.1. Mean annual temperature (^{0}C), rainfall (mm), river discharge (m^{3} sec^{-1}), and fecal coliform (CFU 100ml^{-1}) data

Year	Site no.	Temperature	Rainfall	River discharge	Fecal Coliform
1999	6	7.70	0.80	0.00	362.05
1999	10	10.94	2.73	46.25	43.00
1999	20	10.94	2.73	8.45	95.62
2000	7	9.74	1.73	2052.92	1.50
2000	9	9.91	1.24	2808.94	13.11
2000	10	8.19	1.92	37.72	17.58
2000	11	7.37	0.06	26.11	6.30
2000	14	8.64	2.01	646.86	3.64
2000	15	10.80	7.14	4.83	20.45
2000	16	11.24	2.90	1898.00	19.13
2000	17	4.86	1.30	45.81	1.30
2000	18	8.64	1.82	113.36	28.27
2000	19	8.50	2.09	50.52	12.13
2000	20	8.20	1.85	6.39	208.27
2000	21	9.83	4.40	172.65	3.10
2000	22	7.24	1.07	197.43	3.83
2000	26	11.37	1.12	56.45	53.12
2000	27	5.71	2.95	222.35	9.45
2000	30	11.49	0.50	18.92	8.62
2000	31	2.88	4.73	1795.00	20.00
2000	32	11.04	4.09	3010.00	1.30
2000	33	10.11	0.97	2958.18	1.18
2000	36	7.13	1.23	6.22	71.32
2000	39	7.53	1.28	20.37	15.50
2000	40	12.44	1.04	43.58	6.91
2000	43	10.39	1.61	948.09	9.18
2001	7	8.25	1.50	1565.36	1.75
2001	9	9.14	1.07	2040.38	18.10
2001	10	10.31	2.44	43.17	40.62
2001	11	6.61	0.45	12.52	5.85
2001	14	6.33	2.19	643.47	8.47
2001	15	10.44	10.00	4.29	18.83
2001	16	5.97	2.57	1525.83	25.17
2001	17	3.07	1.21	35.50	1.26
2001	18	7.26	3.73	33.36	6.32
2001	19	6.89	2.36	30.40	10.14
2001	20	10.31	2.44	8.72	80.10
2001	21	8.06	3.96	93.20	5.13
2001	22	7.08	1.08	77.75	3.25
2001	23	9.90	2.38	2.66	1.89
2001	26	9.86	1.80	29.22	86.24
2001	27	3.63	2.15	221.19	6.33
2001	30	9.62	2.38	7.90	9.34
2001	31	5.85	3.33	1528.35	4.71
2001	32	10.84	4.68	1950.91	1.00
2001	33	11.01	2.11	2028.33	1.17
2001	36	7.34	1.21	3.41	77.69
2001	39	5.20	1.49	9.74	3.38

Table C.1. continued

Year	Site no.	Temperature	Rainfall	River discharge	Fecal Coliform
2001	40	10.77	2.05	22.76	5.89
2001	41	13.00	0.11	0.38	4.38
2001	43	9.71	1.37	639.89	5.18
2002	7	8.22	1.95	1902.87	1.43
2002	9	8.45	1.93	2878.33	13.46
2002	10	10.13	2.86	50.05	27.52
2002	11	-5.72	0.00	4.78	4.17
2002	12	1.92	1.77	23.53	4.22
2002	14	3.96	1.47	496.31	9.16
2002	15	10.42	12.98	4.76	20.08
2002	16	6.40	3.61	1823.00	26.00
2002	17	1.74	0.91	36.97	1.05
2002	18	7.56	4.25	75.85	10.96
2002	19	7.52	4.58	40.41	13.96
2002	20	10.02	2.97	9.18	81.38
2002	21	7.25	4.48	186.11	3.71
2002	22	6.47	2.26	70.87	2.31
2002	23	2.66	5.11	91.08	0.71
2002	26	11.10	4.54	39.52	96.62
2002	27	3.81	4.02	295.38	8.80
2002	30	11.13	1.48	20.06	9.82
2002	31	0.91	0.09	1621.11	7.00
2002	32	10.22	4.47	2860.00	3.55
2002	33	7.11	3.81	2248.89	1.00
2002	36	7.63	0.89	5.87	103.01
2002	39	6.16	2.91	30.88	5.15
2002	40	2.20	0.50	20.45	1.00
2002	41	11.47	2.55	0.64	3.53
2002	43	-2.77	0.00	233.50	4.67
2003	7	11.09	0.90	1831.18	4.96
2003	8	6.94	0.00	1.33	1.88
2003	9	9.89	0.76	2456.04	6.17
2003	10	11.17	6.60	58.14	15.19
2003	11	13.99	0.67	29.55	15.07
2003	12	7.37	0.56	37.30	6.09
2003	14	10.84	1.71	488.79	7.50
2003	15	12.23	19.33	4.66	26.80
2003	16	5.30	1.89	1196.04	112.43
2003	17	5.00	1.51	40.63	4.48
2003	18	9.23	2.03	54.28	6.95
2003	19	9.13	3.72	37.63	32.96
2003	20	11.17	6.60	8.44	32.73
2003	21	10.13	3.40	129.47	3.00
2003	22	9.64	3.60	199.66	6.74
2003	25	11.20	13.93	1.81	2.67
2003	26	11.90	1.71	35.24	27.57
2003	27	4.67	1.74	200.11	5.87
2003	28	14.44	0.20	5.81	12.60

Table C.1. continued

Year	Site no.	Temperature	Rainfall	River discharge	Fecal Coliform
2003	30	12.56	1.86	8.07	11.63
2003	31	5.73	3.44	1415.19	19.29
2003	32	12.72	1.92	2490.00	1.11
2003	33	12.04	4.51	2497.89	1.26
2003	36	8.31	1.00	2.60	84.60
2003	38	9.40	57.10	109.10	3.50
2003	39	9.34	1.29	15.13	5.71
2003	40	13.82	0.85	49.55	14.61
2003	41	12.63	2.37	0.75	1.49
2003	43	11.81	2.61	809.43	8.76
2004	1	12.40	1.88	28.88	1.38
2004	2	11.14	2.81	25.67	2.32
2004	3	11.17	2.59	25.49	4.43
2004	4	10.95	3.51	24.59	1.00
2004	5	-4.65	0.00	51.30	2.50
2004	7	9.61	0.89	1803.55	1.71
2004	8	9.34	1.45	1.20	6.91
2004	9	10.18	1.23	2492.55	10.85
2004	10	11.73	1.59	43.97	32.21
2004	11	8.98	0.31	23.98	5.35
2004	12	6.09	1.46	41.83	4.89
2004	13	5.03	13.33	12.13	85.33
2004	14	10.66	2.69	640.07	15.47
2004	15	12.28	14.69	4.60	28.23
2004	16	4.52	4.34	1256.74	68.58
2004	17	4.86	3.41	43.60	1.12
2004	18	9.65	4.19	90.96	10.52
2004	19	9.21	1.89	41.36	17.26
2004	20	11.82	1.55	8.87	34.12
2004	21	9.70	4.54	147.85	16.50
2004	22	6.50	2.78	146.35	8.27
2004	25	11.75	2.90	12.62	6.64
2004	26	13.59	1.93	56.92	71.89
2004	27	4.70	7.18	214.96	6.68
2004	28	13.11	1.73	24.09	17.44
2004	29	11.95	13.73	1.56	16.33
2004	30	12.18	1.10	9.41	19.23
2004	31	0.52	1.23	1450.87	22.09
2004	32	4.53	3.60	1736.67	1.00
2004	33	8.76	2.19	2235.00	1.13
2004	36	8.63	1.03	3.30	97.77
2004	38	11.27	35.50	51.60	16.74
2004	39	8.69	1.36	19.83	5.64
2004	40	11.99	1.50	45.20	10.00
2004	41	12.26	3.03	1.83	1.65
2004	42	14.25	18.90	4.58	194.88
2004	43	11.74	1.61	686.24	4.56
2005	1	6.64	5.17	13.86	1.06

Table C.1. continued

Year	Site no.	Temperature	Rainfall	River discharge	Fecal Coliform
2005	2	7.87	3.61	18.43	1.42
2005	3	7.88	3.47	18.77	15.04
2005	4	9.25	4.01	22.98	1.38
2005	5	4.24	0.59	104.10	8.76
2005	7	8.50	1.22	2056.15	9.15
2005	8	5.63	0.93	1.01	1.73
2005	9	8.52	0.91	2658.44	20.24
2005	10	10.03	1.06	54.30	58.14
2005	11	9.10	2.85	36.94	12.74
2005	12	6.59	1.98	62.58	8.26
2005	13	10.21	4.33	11.64	34.25
2005	14	4.29	0.37	491.29	6.00
2005	15	11.96	16.22	4.96	96.78
2005	16	7.30	2.40	1617.48	236.86
2005	17	4.08	3.58	45.55	1.00
2005	18	8.09	3.67	91.19	10.50
2005	19	9.77	2.25	58.55	20.76
2005	20	9.97	1.01	8.17	72.04
2005	21	8.45	3.15	165.35	15.08
2005	22	7.84	1.58	165.92	7.33
2005	25	13.63	4.20	19.09	5.22
2005	27	5.64	3.74	292.54	10.88
2005	28	10.46	1.44	21.86	27.69
2005	29	9.83	23.79	3.64	34.89
2005	30	8.71	2.37	18.16	15.04
2005	31	2.91	3.65	1633.46	24.23
2005	33	6.21	3.10	2412.86	1.00
2005	34	9.17	7.60	5.69	27.36
2005	35	11.73	1.42	3.04	93.63
2005	36	7.99	1.36	4.83	95.06
2005	37	11.66	2.99	6.12	161.05
2005	38	9.10	22.25	32.43	9.64
2005	39	7.54	1.24	13.36	3.04
2005	40	13.48	2.90	37.12	11.48
2005	41	12.53	2.17	1.03	1.00
2005	42	10.64	48.52	8.81	668.00
2005	43	9.71	1.57	772.59	6.11
2006	1	8.64	1.63	24.26	1.47
2006	2	7.95	1.37	23.29	6.80
2006	3	8.67	1.27	23.73	199.78
2006	4	9.62	1.92	25.72	1.94
2006	5	6.06	0.31	99.72	2.80
2006	6	10.76	0.91	0.36	360.65
2006	7	11.31	1.25	1996.27	8.35
2006	8	11.31	0.24	1.26	6.67
2006	9	10.27	1.36	2788.72	28.47
2006	10	10.88	4.56	64.21	35.31
2006	11	7.72	0.22	22.26	5.24

Table C.1. continued

Year	Site no.	Temperature	Rainfall	River discharge	Fecal Coliform
2006	12	6.31	0.56	39.68	2.44
2006	13	10.41	3.22	12.63	31.36
2006	14	12.10	0.00	779.00	4.00
2006	15	11.21	14.35	4.53	135.05
2006	16	7.96	0.68	1227.71	768.47
2006	17	4.20	2.60	26.27	1.33
2006	18	10.24	4.31	97.41	11.88
2006	19	8.41	2.11	48.52	25.41
2006	20	10.71	4.47	15.04	34.48
2006	21	8.81	4.86	135.93	17.78
2006	22	9.06	2.59	183.93	13.84
2006	24	10.33	1.21	15.06	179.81
2006	25	14.04	1.51	23.86	12.33
2006	27	7.65	3.80	191.12	39.54
2006	28	13.18	2.51	39.15	34.84
2006	29	10.69	15.45	1.98	22.83
2006	30	12.76	2.68	19.67	16.54
2006	31	4.73	1.12	1105.89	11.00
2006	33	10.21	0.23	2331.25	1.00
2006	34	10.60	12.45	9.89	22.75
2006	35	10.08	0.88	3.23	85.48
2006	36	8.59	1.00	4.87	116.54
2006	37	9.76	0.47	6.53	158.95
2006	38	7.16	28.38	51.12	12.31
2006	39	7.73	2.34	29.06	7.00
2006	40	11.73	3.26	51.82	17.23
2006	41	10.51	3.27	2.06	1.12
2006	42	12.50	14.14	3.25	783.21
2006	43	10.32	1.57	688.44	2.92
2007	6	14.26	0.23	0.31	530.90
2007	24	12.52	0.02	8.67	119.15
2007	37	10.58	0.16	5.77	112.28
2007	41	5.98	7.96	6.11	1.08
2008	6	10.11	0.94	0.44	421.56
2008	24	11.38	1.22	11.70	84.25